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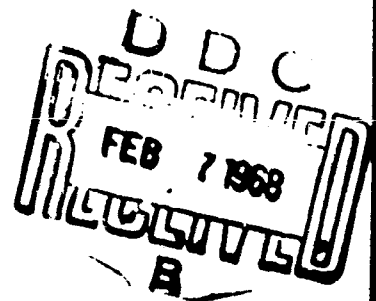
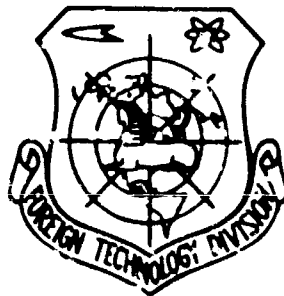
FOREIGN TECHNOLOGY DIVISION



SCIENCE OF AVIATION MATERIAL

by

A. E. Leykin, E. S. Porotskiy and B. I. Rodin



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SCIENCE OF AVIATION MATERIAL

By: A. E. Leykin, E. S. Porotskiy and R. I. Rodin

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A. E. Leykin, E. S. Porotskiy, B. I. Rodin

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ABSTRACT: This textbook is intended for students at tekhnikums. It may also be useful to technicians of the aircraft industry. The book reviews basic characteristics of the most important metallic and nonmetallic materials used in aircraft structures. Methods of investigating alloy properties, flaw detection, heat treatment, thermochemical treatment, and corrosion prevention are described. The authors express their thanks to Docent K. P. Romadin and candidates of Technical Sciences A. I. Samokhotskiy and N. K. Zol'mikova.

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In book are considered basic characteristics of the most important metallic and nonmetallic materials applied in aviation constructions. Given are methods of investigation of properties of alloys and also their inspection (defectoscopy), heat and chemical-heat treatment, and protection from corrosion. Book is text for course of the same name for students of technicums. It will also be useful for average technical staff of industry.

Engineer critics A. I. Samokhotskiy and N. K. Zol'nikova

Editor K. P. Romadin, Cand. Tech. Sciences

PREFACE

Continuous progress of technology requires creation of new materials possessing assigned properties.

In his report to XXII Congress of CPSU N. S. Khrushchev underlined that "...of urgent value is sharp increase of strength and reliability of metals and other materials, in particular, those functioning under conditions of super-high pressures, temperatures, and speeds."

Production of contemporary machines would be inconceivable without use of specially pure metals, high-strength alloys metal ceramics, plastics, and other nonmetallic materials.

This text, written in accordance with program of course by same name, should prepare students of technical schools for correct selection and rational use of different materials for aviation constructions.

Future designer, when designing a new or modernizing existing aircraft, should know how on a technical and economic basis to select necessary materials. Future technologist should know how to select the most rational, in technical-economic respect, variant of technological process of treatment of materials utilized in given construction.

In text are expounded bases of aviation study of materials. In it are considered the most important characteristics of contemporary metallic and nonmetallic materials utilized during production of aviation material. Given are contemporary method of investigation of properties of materials and method of defectoscopy. Methods of heat and chemical-heat treatment of metals and alloys and their protection from corrosion are illuminated.

In first division (Chapters I-IX) are presented bases of metal science; second division (Chapters X-XIV) includes ferrous metals and special alloys; third division (Chapters XV-XX) includes nonferrous metals, alloys, and metal ceramic materials; in fourth division (Chapters XXI-XXII) are illuminated questions of corrosion; last, fifth division, (Chapters XXIII-XXVIII) is devoted to nonmetallic materials.

All mechanical characteristics of materials are expressed in International System of Units [SI] (CM). Besides, in text are given in parentheses dimensions in old units.

Book was written by collective of authors under leadership of A. Ye. Leykin.

Authors express deep gratefulness to K. P. Romadin, Cand. of Tech. Sciences, Docent, A. I. Samokhotski, and N. K. Zol'nikova for valuable remarks and counsels made during creation of this text.

All remarks and proposals for improvement of text should be directed to publishing house "Mashinostroyeniye," (Moscow, B-66, 1 Basmannyy per., 3).

INTRODUCTION

In aviation industry are applied widely various metallic and nonmetallic materials.

Contemporary jet engineering demanded creation of latest heat-resisting metallic alloys and different new nonmetallic materials possessing properties in full measure responding to contemporary conditions of exploitation.

Development of aircraft construction is characterized by creation of constructions of high parameters (tremendous speeds, high gross weight, and others), working under conditions of high pressures, high and very low temperatures, deep vacuum, etc.

Structural materials working in conditions of high temperatures must have high strength and creep strength, must be resistant to thermal shock and oxidation.

During selection of materials for parts of aviation constructions, considered are their density and so-called specific strength, characterized by ratio of strength to specific gravity. As characteristic of strength can be taken one of following properties: ultimate strength, yield point, fatigue limit, modulus of normal elasticity, and other characteristics interesting designer. During the designing of aircraft preference should be given to material possessing greatest specific strength. This will allow one, other things being equal, to increase strength of construction to lower its weight, to increase flying range. Contemporary structural materials applied in aircraft construction have specific strength from 16 to 23 and in certain cases to 30.

Basic direction of creation of new aviation materials is obtaining of

compositions able to work reliably in conditions of high temperatures (for instance, 1200°C and more). Therefore criterion of appraisal and selection of materials of aviation constructions is frequently change of specific strength with increase of temperature.

In contemporary aircraft construction is applied large quantity of various materials, which it is expedient to divide into two basic groups - metallic and nonmetallic materials.

Metallic materials include metals and their alloys. In nature approximately two thirds of all elements are metals. They are divided into ferrous and nonferrous.

Practical value of metals is unequal. Of greatest application in industry are iron and its alloys, constituting group of ferrous metals. Remaining metals and their alloys belong to nonferrous group.

Application of nonferrous metals and alloys is limited by their smaller extent in nature and high cost. Volume of production of ferrous metals is approximately equal to 94% of world production of all metals, whereas production of nonferrous metals constitutes only 6%.

In aviation industry, besides ferrous metals, widely applied are light non-ferrous alloys based on aluminum, magnesium, and titanium. Less widely applied are alloys of copper. Tin, lead, zinc, nickel, and chromium are applied in the form of alloying elements. Besides these are applied alloys based on nickel and refractory metals and also cermet materials.

Development of contemporary aviation technology is intimately connected use of nonmetallic materials: plastics, rubbers, textile, varnish and paint, hermetically sealing and wood materials, and also glues.

Value of some or other nonmetallic materials in aviation industry is changing considerably with development of aviation technology. Thus, if in past one of leading places belonged to wood, then at present first place belongs to plastics, rubber, and different hermetically sealing materials.

In accordance with decisions of December Plenum of Central Committee of the Communist Party of the Soviet Union (1963) on questions of development of production of synthetic materials, in book are specially considered questions of application of polymers in aircraft construction.

Creation of aircraft of successfully surmounting "sound barrier" led to development of latest aviation materials with special properties. Further improvement of

heat-resisting materials will allow us in the very near future to solve also the problem of "thermal barrier," appearing at supersonic speeds of flight.

Science involving general composition, structure, and properties of metals and alloys is called metal science.

Founders of scientific study of metals are Russian scientists P. P. Anosov and D. K. Chernov. Further development of metal science was promoted by work of N. S. Kurnakov, A. A. Bagov, A. A. Bochvar, N. T. Gudtsov, G. V. Kurdyumov, Serbi, Austen, Osmond, Tamman, Martens, and others.

In study of materials properties of materials are considered in interaction with their structure: distribution and character of movement of electrons, atomic arrangement in space, dimensions and form of crystal formations.

Knowing structure of material, one can in known measure judge its properties and its fitness for work under some or other conditions.

Knowledge of properties and possibilities of application of different aviation materials has very important value in all stages of designing, creation, and exploitation of new aviation technology.

S E C T I O N O N E

PRINCIPLES OF METAL SCIENCE

CHAPTER I

STRUCTURE AND CRYSTALLIZATION OF METALS

§ 1. Structure of Metals

Metals are chemical elements possessing metallic luster, high electrical and thermal conduction, opacity in hard and liquid state, plasticity, and crystal structure.

As any substance, metals consist of atoms. Atoms of different metals differ from each other by number of electrons moving in electron shells and quantity of protons and neutrons forming atomic nuclei.

Atoms of the same element differing from each other only by number of neutrons in nucleus are called isotopes. Isotopes are varieties of the same atom.

Electrons move in circular or elliptic orbits. Electrons located in outer orbits are called valence electrons. Valence electrons are bound weakly with nucleus, and easily abandon the atom, crossing to outer orbits of other atoms.

A clear representation of metals and their structure is given by periodic system of elements of D. I. Mendeleev.

Of the 103 elements of the Mendeleev periodic system more than 70 are metals. Atomic number in periodic system is determined by quantity of protons (electrons) in atom.

For instance, for iron, occupying 26th place in table, in nucleus are concentrated 26 protons, and around it move 26 electrons in orbits. Elements in one group of Mendeleev table possess related properties.

For elements in one period properties gradually are changed with their distance from each other, the character of this change being repeated in following row (line of table). Neighboring elements in one period possess relatively close properties.

Metal in solid state constitutes totality of positively charged ions with electrons distributed between them which move freely from ion to ion, forming "electron gas" (Fig. 1.1).

Such bond between atoms is called metallic. It explains such properties characteristic and inherent to only metals as high plasticity, electrical conductivity, and thermal conductivity.

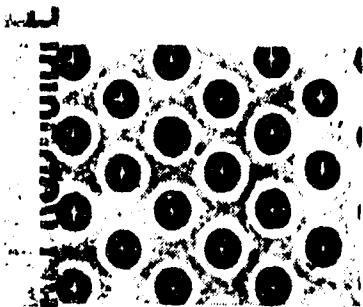
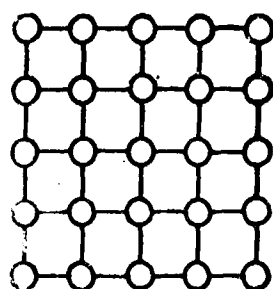


Fig. 1.1. Structure of metals. At lattice points are positively charged ions. In spaces are free electrons.

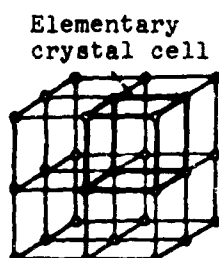
Crystalline and amorphous bodies are distinguished. In an amorphous body (glass, rosin) atoms are located chaotically, without any system. In crystalline substance atoms are disposed in defined geometrically regular order at defined distance from each other. Metals and their alloys are crystalline bodies.

In metals atoms (ions) are located in strictly defined order, forming so-called crystal space lattice (Fig. 1.2).

In Fig. 1.2a is shown location of atoms in one of crystallographic planes. Multiple repetition of crystallographic planes located in parallel gives



a)



b)

Elementary crystal cell

representation of crystal space lattice, points of which are locations of atoms (Fig. 1.2b). In order to have an idea of atomic-crystal structure of given substance it is sufficient to depict one of its elementary crystal cells. The most simple is cell of cubic lattice.

Fig. 1.2. Atomic arrangement (ions) of crystalline substance. a) crystallographic plane; b) crystal space lattice.

Types of crystal lattices. Atoms of various metals form unequal crystal

lattices. Most frequently encountered are three types of lattices.

First type of lattice: b o d y - c e n t e r e d c u b i c. Atoms of metal in such lattice are at vertexes and center of cube. Every atom is surrounded by eight nearest "neighbors" (Fig. 1.3a). Having such lattice are α -iron, vanadium, tungsten, molybdenum, manganese, chromium, niobium, and others.

Second type of lattice: f a c e - c e n t e r e d c u b i c (Fig. 1.3b). Atoms of metal in it are located at vertexes and in center of cube faces. Such lattice

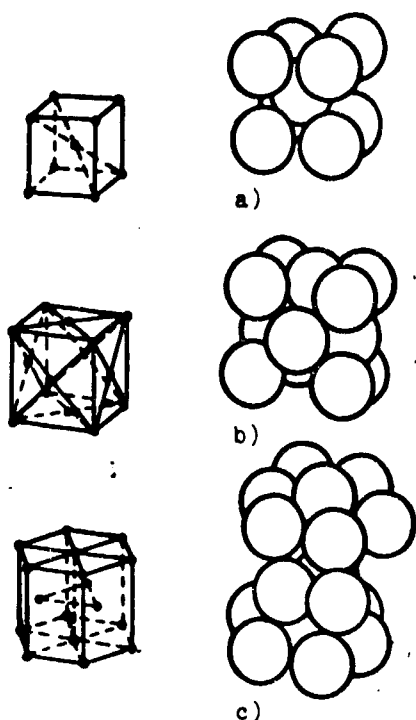


Fig. 1.3. Crystal lattices.
a) body-centered cubic, b)
face-centered cubic, c)
close-packed hexagonal.

belongs to γ -iron, aluminum, lead, nickel, copper, and others.

Third type of lattice: close-packed hexagonal (Fig. 1.3c). It is encountered in zinc, magnesium, cadmium, beryllium, α -titanium, and α -cobalt.

Dimensions of crystal lattice are characterized by lattice parameters or so-called "constants." Parameters determine basic dimensions of elementary crystal cell. Thus, cubic lattice is characterized by one parameter - length of rib of cube a ; hexagonal lattice is characterized by two parameters a and c or ratio c/a .

Parameter of crystal lattice is measured in nonometers ($1 \text{ Nm} = 1 \cdot 10^{-9} \text{ m}$).¹ Parameters of crystal lattices of metals usually are within limits 0.28 to 0.60 Nm.

Density of packing of atoms in crystal lattices is high. Thus, in body-centered cubic lattice atoms occupy 68% of space, and in face-centered cubic lattice 74% of space belongs to atoms.

Allotropy of metals. Allotropy or polymorphism of metals is their property to have different structure at various temperatures.

Process of transition from one type of crystal structure to another is called allotropic transformation or recrystallization.

Allotropic transformations of metal are accompanied by thermal effect, i.e., by emission (during cooling) or absorption (during heating) of heat and take place at constant temperature.

Different allotropic modifications of elements are customarily designated by Greek letters α , β , γ , δ , etc., where letter α designates that allotropic modification which exists at the lowest temperature. Allotropy is possessed by a series of technically important metals - iron, tin, cobalt, manganese, titanium, and others.

¹Parameters of crystal lattices were measured previously in kilo-x units ($1 \text{ kXu} = 1 \cdot 10^{-10} \text{ m} = 0.1 \text{ Nm}$).

Table 1. Allotropic Forms of Metals

Metal	Allotropic form	Range of temperatures of stable state	Crystal lattice
Iron	Fe_{α}	to 910°C	Body-centered cubic
	Fe_{γ}	and 1400-1539°C 910-1400°C	Face-centered cubic
Tin	Sn_{α}	To 18°C	Diamond type cubic
	Sn_{β}	From 18°C to melting point 232°C	Body-centered tetragonal
Cobalt	Co_{α}	To 477°C	Close-packed hexagonal
	Co_{β}	From 477°C to melting point 1490°C	Face-centered cubic
Manganese	Mn_{α}	To 742°C	Complex cubic
	Mn_{β}	742-1192°C	The same
	Mn_{γ}	From 1192°C to melting point 1244°C	Face-centered tetragonal
Titanium	Ti_{α}	To 882°C	Close-packed hexagonal
	Ti_{β}	From 882°C to melting point 1660°C	Body-centered cubic

Anisotropy of crystals. In separate crystals mechanical and certain other properties are different in various directions. This property of crystals is called anisotropy. Anisotropy is explained by defined atomic arrangement in crystal: in one direction there always are more of them than in the other (Fig. 4a).

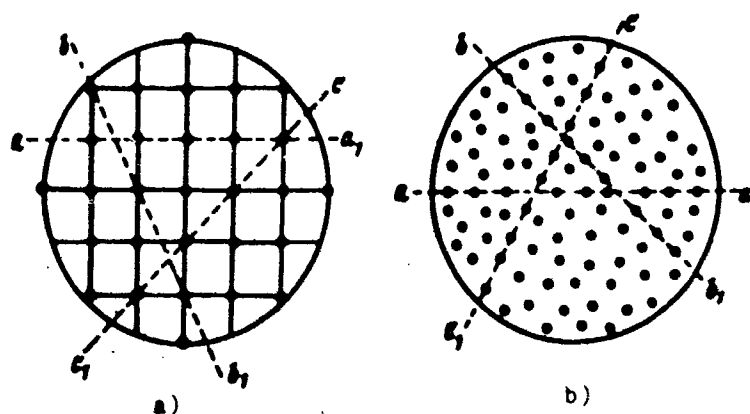


Fig. 1.4. Atomic arrangement. a) in crystalline body, b) in amorphous body.

Amorphous bodies are isotropic, i.e., all their properties are identical in all directions. This is explained by the fact that amorphous bodies in different directions have identical density of packing of atoms (Fig. 1.4b).

Metals are polycrystalline bodies, i.e., consisting of large quantity of variously oriented small crystals (Fig. 1.5). Therefore properties of metal will be

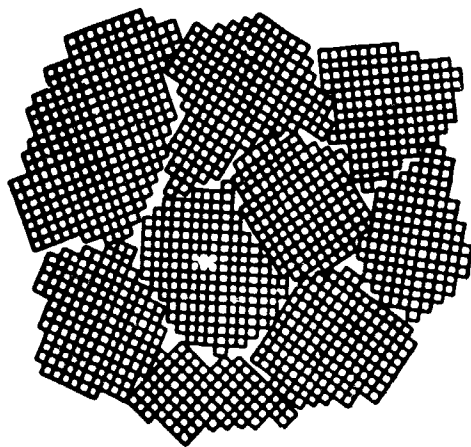


Fig. 1.5. Structure of polycrystalline body.

approximately identical in all directions. This phenomenon is called quasi-isotropism (apparent isotropism). But this seeming isotropism of metal disappears if through some treatment crystals are given defined orientation.

In crystals are so-called glide planes or cleavage planes, over which shift atoms (ions) of crystal lattice during mechanical influence on crystal.

Plastic deformation under action of forces most easily occurs on planes most closely packed with atoms.

Real structure of metallic crystals. Investigations of the recent years reveal crystals of metals are deflections from ideal location of atoms. It was revealed that mechanical and physical properties and also processes occurring in metals depend upon imperfection of structure of their crystals.

Atoms at points of crystal lattice are located in regular sequence. However, certain atoms are displaced in regular sequence. However certain atoms are displaced to interstices of lattice (so-called translations), and at certain lattice points atoms are absent (so-called vacancies) (Fig. 1.6).

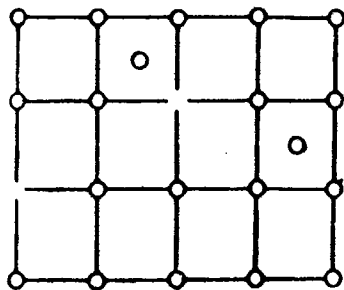


Fig. 1.6. Free points and atoms displaced into interstice.

With increase of temperature thermal agitation of atoms - average amplitudes of their oscillations - are increased and number of vacancies and displacements increases. However, number of them even at a temperature close to fusion point does not exceed 2%.

Transition of atoms to interstice, formation and shift of vacant sites, and distortion of lattice around them are causes of disturbance of regular geometric crystal structure. Disturbance of crystal lattice may

also be the result of influence of impurity atoms.

In structure of real crystals are more considerable defects of structure. Thus, crystals of metal in many cases consist of large number of regions having dimension of order of 1 micrometer (1 micron) and turned relative to each other by thousandths of a radian (tenths of a degree). These are separate regions having regular packing of atoms, called blocks (Fig. 1.7). On boundary between blocks, owing to their disorientation, packing of atoms is distorted.

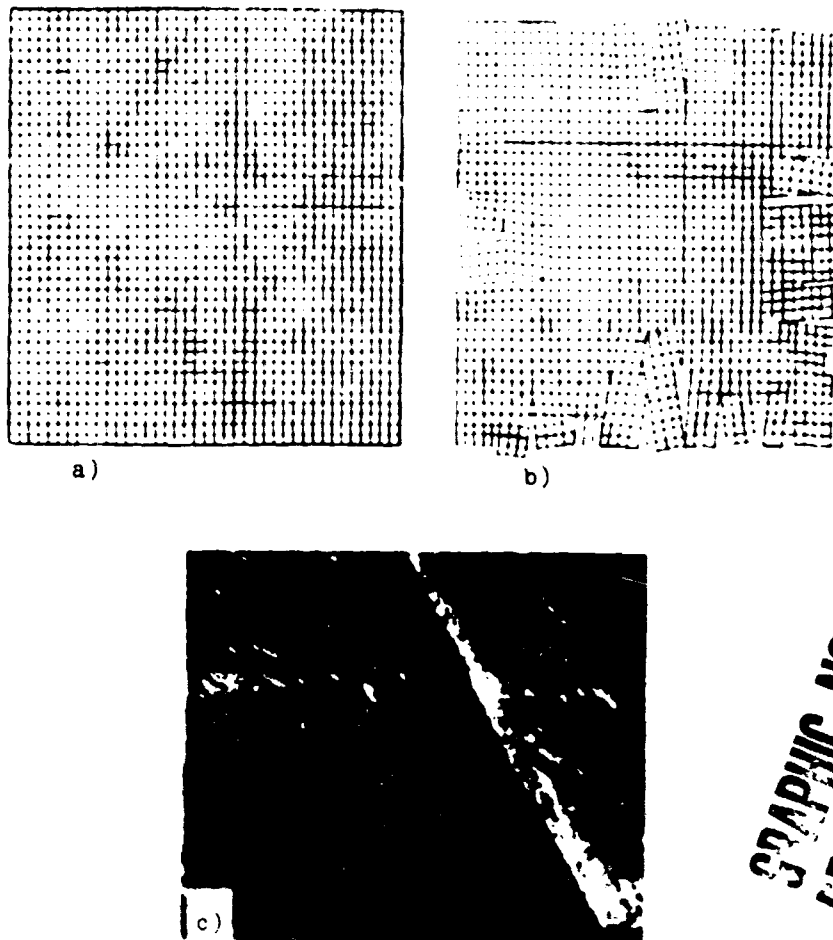


Fig. 1.7. Structure of crystals. a) structure of ideal crystals, b) structure of real crystals, c) photograph of block structure, $\times 20,000$.

Thus, crystal constitutes unique mosaic of blocks. Such structure is called block or mosaic. Metals usually are polycrystalline bodies, i.e., consist not of separate crystal but a huge number of crystals (grains) with different mutual orientation of lattices. Owing to this, on boundary between separate grains or blocks atomic arrangement turns out to be less correct than that inside every grain.

Since surface layer of grain (grain boundary) abounds in defects, it differs essentially from core both in properties and also in chemical composition.

In real crystals are imperfection of crystal structure, called dislocation or translation. Dislocation is linear imperfection of crystal, forming boundary of nonuniform shift or rotation of crystal lattice. Dislocation forms as a result of deficiency (surplus) atom in given atomic row, which may cause elastic displacement of considerable quantity of atoms relative to their normal position of equilibrium and dispersion of vacancies by certain section of atomic row.

We distinguish edge and screw dislocations (imperfections). In Fig. 1.8 is shown diagram of formation of edge dislocation. Dislocations of crystal lattice can be formed in process of growth of crystals, during inosculation of grains and blocks with relatively small angle of orientation, during defined accumulation of vacancies, and during deformation of metal.

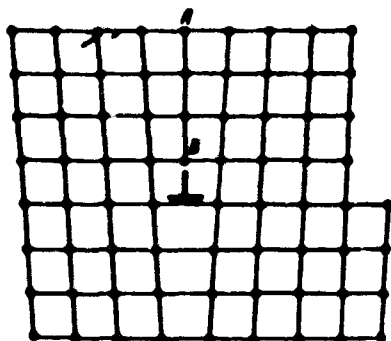


Fig. 1.8. Diagram of atomic arrangement during edge dislocation.

Theory of dislocation at present is applied widely for explanation of series of phenomena occurring in metals. Thus, in examining questions of strength of plastic deformation, diffusion and certain others theory of dislocations is used.

§ 2. Crystallization of Metals

Crystallization is process of formation of crystals. We distinguish primary and secondary crystallization. During primary crystallization crystals form from liquid in process of solidification of metal. Secondary crystallization is combined with change of crystal structure of metal or alloy in solid state.

Curves of cooling. For study of process of crystallization we plot curves of cooling, showing change of temperature with time as molten metal cools.

In Fig. 1.9 is depicted process of crystallization of pure metal. In order to cause crystallization liquid metal must be cooled to temperature t_{np} , equilibrium temperature of crystallization of metal t_{mz} . Difference between equilibrium temperature of crystallization t_{mz} and temperature t_{np} , at which under given conditions occurs process of crystallization, bears the name of degree of cooling.

Amount of cooling depends on nature of metal and on rate its cooling. Other

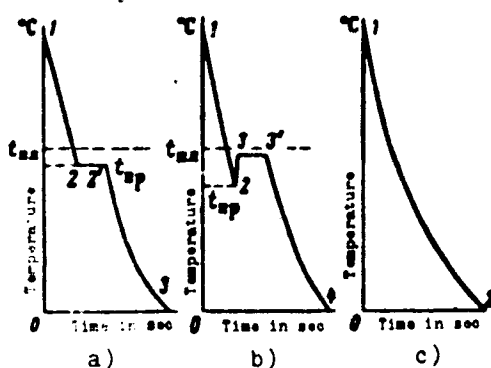


Fig. 1.9. Curves of hardening. a) crystalline body; b) crystalline body with loop of cooling; c) amorphous body.

At point 2, starts process of crystallization, which continues to point 2'. At moment corresponding to point 2' crystallization stops and entire metal crosses from liquid to solid state.

Transition of pure metals from liquid to solid state occurs as a result of loss of energy of motion by separate atoms. These atoms in relation to one another take position peculiar to their crystal lattice.

At the time of crystallization heat removal is compensated by emanated latent heat of crystallization, and therefore on curve appears horizontal section 2-2'. Section 2'-3 on curve corresponds to cooling of hardening metal.

Amount of cooling for certain metals can be very great, attaining several tens of degrees. For such metals on curve of cooling not infrequently is observed a loop (Fig. 1.9b). Owing to intense generation of heat crystallization, temperature in the beginning intermittently is increased and then remains constant to full hardening of metal.

Amorphous substance hardens gradually owing to decrease of mobility of its particles, and curve of its cooling over its entire extent goes smoothly (Fig. 1.9c).

Process of hardening of amorphous substances takes place without temperature stops, i.e., without critical points.

Mechanism of crystallization. Crystallization, starting with cooling, does not occur instantaneously over entire volume but is developed gradually. It consists of two elementary processes:

- a) onset of nuclei or centers of crystallization;
- b) growth of crystals from these centers.

things being equal, amount of cooling becomes greater the more complicated the lattice of metal and the higher the rate of cooling.

For majority of metals amount of cooling turns out to be very insignificant and is not detected under normal conditions of plotting of curve of cooling (Fig. 1.9a).

Section 1-2 of curve of cooling corresponds to cooling of metal in liquid state to beginning of crystallization. At temperature t_{np} ,

These processes occur simultaneously during crystallization.

Centers of crystallization are either hardened minute particles of metal or hard impurities in liquid metal. In the course of process of crystallization occurs both the onset of new centers of crystallization and growth of crystals (Fig. 1.10). In the process of crystallization, while growing crystal is surrounded by liquid, it has regular form. However, through collision and insculcation of crystals their regular form is disturbed.

After hardening of metal, there are obtained crystals of irregular shape, boundaries of which most frequently take round outlines. Such crystals are called grains or crystallites. Inside every grain is observed defined orientation of crystal lattice differing from orientation of crystal lattices of neighboring grains. Sometimes growth of crystals takes three directions, so that crystallite formed as

a result of crystallization has arborescent form. These crystals are called dendritic (Fig. 1.11).

Properties of metals and alloys in considerable measure depend on dimensions of grains. Metals having fine-grained structure possess higher mechanical properties and better workability than metals with big grains.

Quantitatively the process of crystallization can be characterized if two quantities are known: rate of onset of centers of crystallization and rate of their growth.

Rate of onset of centers of crystallization is quantity of nuclei appearing in unit of volume in 1 sec, and is designated $[n.c.]$ (u.g.) (number of centers).

Rate of growth of crystals constitutes linear increase of growing face of appearing crystal and is designated $[n.g.]$ (c.p.) (rate

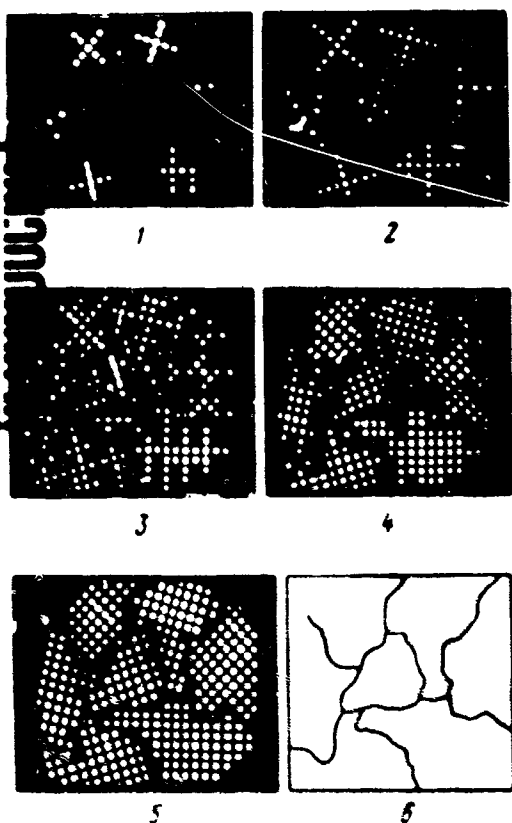


Fig. 1.10. Diagram of process of formation of crystals. 1 - first crystal formed; 2, 3, 4 - number of crystals increased; 5 - crystals came in contact in process of growth; 6 - form of hardened metal.

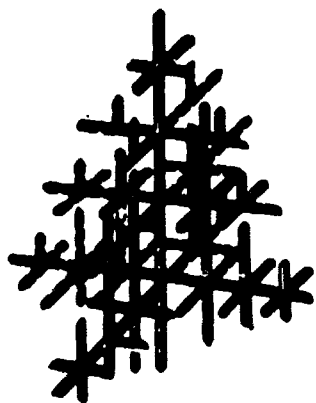


Fig. 1.11. Dendritic form of crystal per N. K. Chernov.

of growth of crystals).

Both these quantities depend on degree of cooling (Fig. 1.12). With increase of degree of cooling, number of centers of crystallization and linear crystallization rate first grow and then decrease. With slight cooling (line I), number of engendered centers and crystallization rate are small and big crystals are formed.

With strong cooling (line II), when crystallization rate attains maximum and number of centers of crystallization engendered in unit of time is comparatively small, crystals of medium size are formed. With very great degree of cooling (line III), minute crystals are formed.

Modification. At present in production of ferrous and nonferrous metals there is widely practiced the process of artificial control of dimensions and form of grains by introduction to molten metal of insoluble substances. This process is

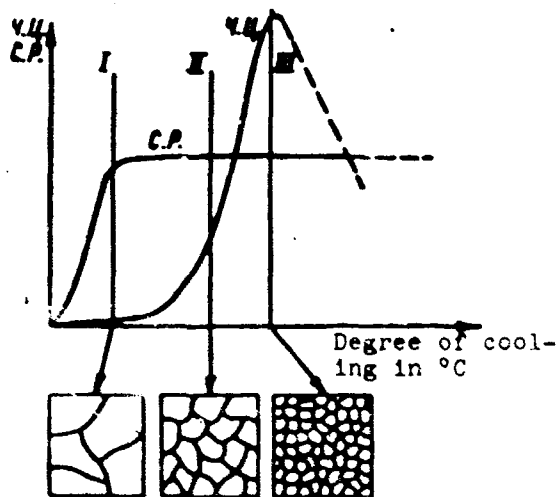


Fig. 1.12. Influence of degree of cooling on rate of onset of centers (n.c.) and rate of growth of crystals (r.g.).

called modification. Through modification, thanks to equal distribution of mentioned substances (modifiers) over entire volume of liquid metal, grains are smaller and of somewhat different form. Such change of structure of metal improves its mechanical and technological properties.

As modifiers are applied: for steel - powder of aluminum oxide; for cast iron - alloys of iron and chromium or silicon and also magnesium; for silumin - sodium, etc.

Structure of steel ingot. In Fig. 1.13 is presented diagram of structure of steel ingot. It consists of three zones: fine-crystalline surface zone 1, zone of columnar crystals 2 and zone of equiaxial crystals 3 located in center of ingot. At top of ingot is shrinkage cavity 4.

Owing to intense cooling, directly at walls of casting mould is formed a shell of fine-crystalline structure. Between walls of casting mould and this shell is

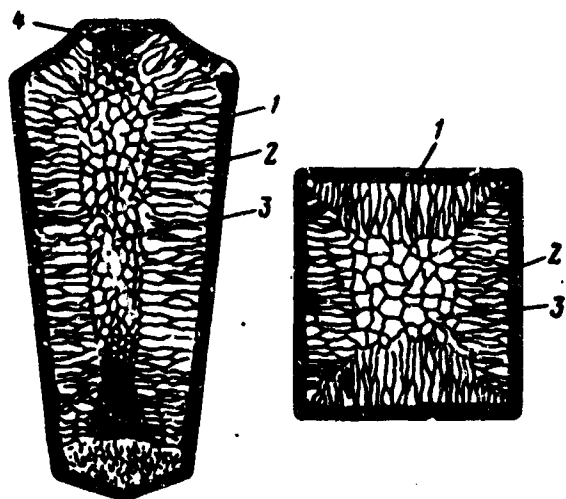


Fig. 1.13. Diagrams of longitudinal and cross sections of an ingot.

created air gap, heat radiation decreases, and this favors growth of crystals. From periphery toward center grow big columnar crystals. In central part of ingot, hardening last, conditions of heat radiation are changed and in it are formed equiaxial crystals of various dimensions. But this part of ingot is contaminated by harmful impurities - sulfur, phosphorus, which lowers its quality. Shrinkage cavity is formed due to decrease of volume of metal during its hardening.

CHAPTER II

PROPERTIES OF METALS AND ALLOYS AND METHODS OF THEIR TESTING

§ 1. Properties of Metals

Application of metals in technology is conditioned by their properties. For correct selection of material and also for establishment of technological conditions of its treatment during manufacture of different parts, it is necessary to know physical chemical, mechanical and technological properties of materials and methods of their determination.

To physical properties pertain: color, specific gravity, melting point, thermal conductivity, thermal expansion, electrical conductivity, magnetic properties, and others.

By chemical properties of metals is understood their ability to interact with environment and with other elements in alloy.

For practical application of metals the following chemical properties are most important: oxidizability, solubility, and corrosion resistance. Questions of oxidizability and corrosion resistance are considered later.

Mechanical properties of metals characterize its ability to resist external stresses. This ability appears in various measure, depending upon form of stress and method of its application.

To mechanical properties pertain strength, rigidity, elasticity, plasticity, hardness, impact strength, and creep.

Strength - property of metals to resist beginning and development of plastic deformation and destruction under action of external forces.

Rigidity - ability of metals to resist elastic deformation.

Elasticity - property of metals to restore initial form after cessation of influence of external forces causing change of form.

Plasticity - irreversible property of metals to be deformed without destruction under action of loads.

Hardness - property of metals to resist penetration in them of other more solid bodies.

Impact strength - ability of metals to resist to impact loads without destruction.

Brittleness - ability of metals to be destroyed without noticeable plastic deformation.

Fatigue strength - property of metals to sustain large number of repeated variable loads without being destroyed. Fatigue is property opposite fatigue strength.

Creep - property of metals to be slowly and continuously plastically deformed during prolonged influence of loads.

Of greatest value are such mechanical properties of metals and alloys as strength, hardness, and plasticity. Impact strength has value for parts working under impact loads. Fatigue strength has value for parts subject to loads varying in magnitude and direction. Creep has important value for parts subject to prolonged load at high temperatures.

Technological properties of metal characterize its ability to be processed in hot and cold states.

To technological properties pertain: fluidity, casting shrinkage, hot- and cold-pressure workability, weldability, hardenability, and workability.

§ 2. Mechanical Tests of Metals

Under the action of loads appearing in process of exploitation of machines and mechanisms occur elastic or plastic deformations of parts. Essence of deformation of metal consists in change of dimensions and form.

Elastic deformation is that which disappears after removal of load. Plastic or residual deformation is that remaining after removal of load.

We distinguish three forms of application of load: static, dynamic, and oscillatory. Static load is that which grows smoothly or remains constant during prolonged time. Dynamic load is characterized by instantaneous (shock) application of force. Oscillatory loads are divided into variables (when applied force changes

in magnitude) and sign-alternating (which periodically change both in magnitude and direction).

Resistivity of material to these loads is unequal. When selecting material for manufacture of some or other structural part, one must consider resistivity of materials to different loads. For determination of properties of material characterizing its resistivity to various loads different methods of testing have been divided.

Basic forms of mechanical tests of metals and alloys applied in aviation industry are for tensile strength, hardness, impact, fatigue strength, and also tests at raised temperatures.

Tensile Test

Tensile test of metals is applied very widely in industry. This is explained by the fact that it enables one to determine strength and plastic properties of metals and alloys.

For carrying out of tensile test are necessary standard samples of tested material of cylindrical or flat form (Fig. 2.1a, b) and rupture-test machine.

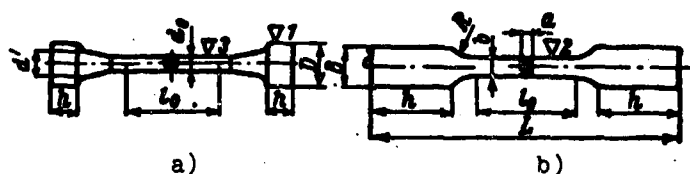


Fig. 2.1. Standard samples for tensile test. a) cylindrical, b) flat, h - length of head, a - thickness of flat sample, b - width of flat sample, l_0 - length of working or design part of sample, L - overall length of sample.

Samples with round cross section are prepared from forgings and rod material or are cast. Flat samples are prepared from sheet materials.

Samples consist of working part and heads, intended for fastening them in jaws of rupture-test machine.

Samples are subdivided into normal and proportional (short and long) types.

Diameter of working part of normal cylindrical sample is 20 mm. Design length for long samples is equal to ten diameters of sample, and for short ones it equals five diameters.

Nonstandard sample can have arbitrary cross section but defined effective length, which is calculated by formulas $l_0 = 11.3\sqrt{F_0}$ for long sample and $l_0 = 5.65\sqrt{F_0}$ for short sample, F_0 being area of cross section of sample in mm^2 . Test is produced on special rupture-test machines (Fig. 2.2).

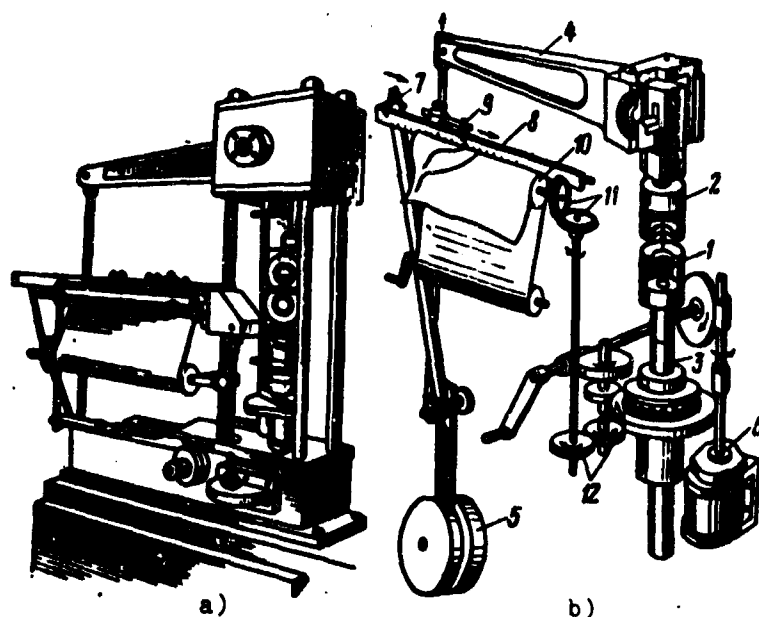


Fig. 2.2. Rupture-test machine IM-4R. a) general form, b) diagram. 1 and 2 - clamps, 3 - screw of loading mechanism, 4 - level, 5 - pendulum, 6 - electric motor, 7 - pointer, 8 - scale, 9 - pen for recording diagram of extension, 10 - diagram drum, 11 and 12 - gears.

All rupture-test machines have loading and self-measuring mechanisms and also device for automatically recording diagram of test.

Tested sample is secured in clamps of rupture-test machine and subjected to load.

Under action of gradually increasing load, sample is extended to destruction.

Stretching force creates stress in tested sample and causes its extension. Stress is load per unit of area of cross section of part (sample). When stress exceeds strength of sample, it fails. Through tensile test are determined characteristics of strength (proportional limit, plastic limit, yield point, ultimate strength) and characteristics of plasticity (elongation per unit length and reduction of area).

Proportional limit $\sigma_{\text{пл}}$ is stress to which lengthening of sample is increased proportionally to applied loads:

$$\sigma_{\text{пл}} = \frac{P_p}{F_0} \text{ [N/m}^2 \text{ (kgf/mm}^2 \text{)]},$$

where P_p - load corresponding to proportional limit in newtons; F_0 - initial area of cross section in m^2 .

Earlier load was measured in kgf and area of mm^2 . Therefore mechanical stress were measured in kgf/mm^2 or in kgf/cm^2 . In system of International units the universal unit of mechanical stress is newton per square meter (N/m^2).

In those cases when systematic unit of mechanical stress is small, one should apply multiple units of stress - kilonewton per square meter ($1 \text{ kN/m}^2 = 10^3 \text{ N/m}^2$), meganewton per square meter ($1 \text{ MN/m}^2 = 10^6 \text{ N/m}^2$): $1 \text{ kgf/mm}^2 = 10^7 \text{ N/m}^2 = 10 \text{ MN/m}^2$.

Plastic limit σ_{pl} is stress at which for the first time are obtained residual elongations of specified magnitude (usually 0.002% of calculated length of sample):

$$\sigma_{\text{pl}} = \frac{P_e}{F_0} [\text{N/m}^2 (\text{kgf/mm}^2)],$$

where P_e is load corresponding to elastic limit in newtons.

It is necessary to consider that for the majority of plastic metals and alloys magnitude of plastic limit is close to magnitude of proportional limit.

Yield point (physical) σ_T is stress at which, in spite of deformation, load either is not changed or is changed insignificantly:

$$\sigma_T = \frac{P_T}{F_0} [\text{N/m}^2 (\text{kgf/mm}^2)],$$

where P_T is load corresponding to yield point (N).

Yield point (conditional) $\sigma_{0.2}$ is stress at which residual elongation of sample is equal to 0.2% of its initial length:

$$\sigma_{0.2} = \frac{P_{0.2}}{F_0} [\text{N/m}^2 (\text{kgf/mm}^2)],$$

where $P_{0.2}$ is load corresponding to conditional yield point.

Yield point indicates loss by material of elastic properties.

Ultimate strength σ_B is conditional stress, corresponding to the biggest load preceding destruction of sample. Ultimate strength is defined as ratio of the biggest load P_B noted during test of sample to initial area of its cross section F_0 :

$$\sigma_B = \frac{P_B}{F_0} [\text{N/m}^2 (\text{kgf/mm}^2)],$$

Real stress at failure σ_z is defined as ratio of load at the time of failure P_z to area of cross section in neck of sample F_1 :

$$\sigma_s = \frac{P_s}{F_1} [N/m^2 (kgf/mm^2)].$$

Ultimate strength of different metals is different. Thus, for instance, cast iron has ultimate strength of 200-250 MN/m² (20-25 kgf/mm²); low-carbon steel, 300-500 MN/m² (30-50 kgf/mm²); and special steel, 600-2000 MN/m² (60-200 kgf/mm²).

Knowledge of strength characteristics of different materials allows designers to select correctly material for manufacture of any parts of aviation material.

Elongation per unit length δ is increase of unit of length of sample expressed in a percentage.

Elongation per unit length is determined by the formula

$$\delta = \frac{l_1 - l_0}{l_0} \cdot 100\%,$$

where l_0 - initial length of sample in mm; l_1 - length of sample after extension in mm.

Difference $l_1 - l_0$ is absolute elongation and is designated Δl (mm).

Absolute elongation does not completely characterize plastic properties of metal, since it depends on length of sample. Elongation per unit length allows one to compare plasticity of different metals outside dependence on length of test samples.

Since ratio of calculated length to diameter for long sample is equal to 10 and for short one is 5, elongation per unit length is designated δ_{10} and δ_5 .

Reduction of area ψ is reduction in area of cross section of sample at point of failure, expressed in percentage of initial cross section:

$$\psi = \frac{F_0 - F_1}{F_0} \cdot 100\%,$$

where F_0 - initial area of cross section of sample in mm²; F_1 - area of cross section of sample after failure in mm².

Elongation per unit length and reduction in area characterize plastic properties of materials, which permit one to judge their ability to be processed by forging, stamping, rolling, etc.

Various metals have different plasticity and consequently different elongation per unit length and reduction of area.

For brittle metals elongation per unit area δ and reduction of area ψ are close to zero; for plastic metals they attain several tens of percents.

Characteristics of properties of metals can be determined by means of diagram of extension, which is recorded automatically by special instrument. In the course of test on this diagram (Fig. 2.3) on vertical axis are plotted values of loads P and on horizontal axis are plotted absolute elongations Δl .

In the beginning, up to point P_p , corresponding to proportional limit, on diagram of extension is rectilinear section, indicating that elongation of sample increases proportionally to applied load. Up to proportional limit in metal appear only elastic deformations.

Then, with increase of load, on diagram appears curvilinear section, indicating disturbance of proportionality between elongation and stress. This load P_e corresponds to elastic limit. With this load, in metal there start to appear permanent deformation. With further increase of load to P_c , on diagram appears horizontal section. With this load sample is increased in length (flows) without increase of load. Load P_c corresponds to yield point.

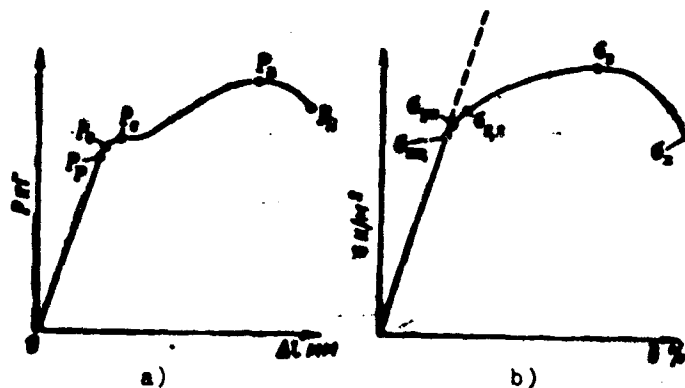


Fig. 2.3. Diagram of extension of low-carbon steel. a) on coordinates "load - deformation," b) on coordinates "stress - elongation per unit length."

If during extension of metal no horizontal site is formed, then as load of yield point is taken that load which causes residual elongation equal to 0.2% of initial length of sample.

Metal in process of deformation is strengthened, and for further extension it is necessary to increase load. The biggest value of load on sample during test P_p corresponds to ultimate strength. With this load in sample starts local narrowing, and so-called neck is formed. Load drops in connection with this, and finally, at



Fig. 2.4. Change of sample as a result of extension. a) sample before test, b) sample after test.

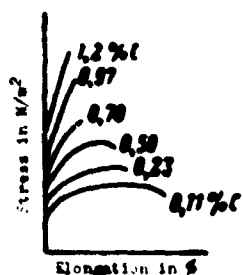


Fig. 2.5. Diagram of extension for steel with different carbon content.

point P_2 sample fails.

After formation of neck, further elongation of sample occurs mainly over length of neck, other part of sample being practically unextended (Fig. 2.4).

To exclude influence of dimensions of sample on coordinates "stress σ - elongation per unit length δ ," as shown in Fig. 2.3b.

Low plastic and brittle metals during extension behave differently than plastic metals, and for them diagram of extension bears another character (Fig. 2.5).

Hardness Test

Test of metals and alloys for hardness is very important and wide-spread form of mechanical test.

From hardness numbers it is possible with certain approximation to judge tensile strength of metal, its wear resistance, and machinability.

Test for hardness is not accompanied by destruction of part, is produced quickly, and does not require cumbersome and complicated machines.

Inasmuch as during determination of hardness surface layers of metal are tested, then for production of correct result surface of metal must not have such defects as scale, decarbonized layer, nicks, big scratches, etc.

Majority of methods of determination of hardness is based on principle of indentation. Here hardness can be determined:

- by magnitude of surface of imprint due to indentation of steel ball through test on Brinell press;

- by depth of imprint through indentation of diamond cone or steel ball during test on Rockwell instrument;

- by magnitude of surface of imprint due to indentation of diamond pyramid during test on Vickers instrument.

Less wide-spread are methods of determination of hardness founded not on indentation but on scratching, swinging of pendulum, elastic rebound, and other principles.

Measurement of hardness by Brinell method. Determination of hardness by this method is based on indentation of tested material by steel ball under action of load. As a result of indentation by ball, on surface of sample appears spherical imprint (Fig. 2.6a).

Diameter of imprint is measured by special magnifier (Fig. 2.6b) in two mutually perpendicular directions, and for determination of hardness average is taken from obtained magnitudes of diameters of imprint. Sample should be so located that distance from center of imprint to edge of sample is not less than two diameters of imprint to prevent "buckling" of edge of sample and distortion of results. It is necessary to make every subsequent measurement at distance of not less than two diameters from preceding imprint. Selection of diameter of ball is made in accordance with thickness of tested article. Thus, for thickness of article of more than 6 mm is applied ball of 10 mm, for thickness of article from 6 to 3 mm - a ball of 5 mm is used, for thickness of article of less than 3 mm - a ball of 2.5 mm is used. So that values of hardness be identical during use of balls of different diameter, it is necessary to observe requirements of so-called law of similarity, according to which ratio of diameters of imprint and ball should be constant:

$$\frac{d}{D} = \text{const.},$$

where D - diameter of ball in mm; d - diameter of imprint in mm.

For observance of this relationship it is necessary that between load P and diameter of ball D there also exist defined relationship:

$$\frac{P}{D^2} = \text{const.}$$

Load is considered selected correctly if the relationship $0.2D < d < 0.6D$ is observed.

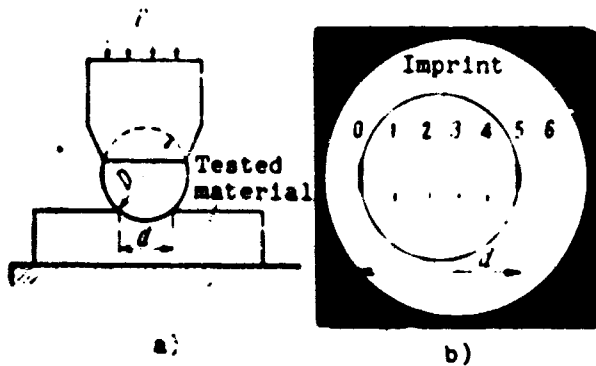


Fig. 2.6. Diagram of test of metals for hardness by Brinell method. a) formation of imprint, b) measuring imprint.

In Table 2 are given norms for tests by Brinell method, from which is selected magnitude of load and diameter of ball in dependence upon properties of tested metal.

Measure of hardness per Brinell is ratio of load P acting on ball to surface of imprint F

$$HB = \frac{P}{F} = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} [N/m^2 (kgf/mm^2)].$$

Brinell hardness is designated HB, expressed in N/m^2 (kgf/mm^2), and determines average normal stress per unit of surface of imprint. Brinell hardness may be expressed by magnitude of diameter of imprint. Indentation of ball in tested metal is done on special instrument.

Table 2. Selection of Parameters During Determination of Hardness on Brinell Instrument

Metals	Hardness HB		Relationship between load P and diameter of ball D	Thickness of sample, mm	Diameter of ball, mm	Load P		Holding under load, sec	
	N/m^2	kgf/mm^2				N	kgf		
Ferrous metals	1000—	100—	$P=30D^2$	Above 6	10	30 000	3000	10	
	4300—	430—		6—3	5	7 500	750	10	
	1000—	100—		Below 3	2,5	1 875	187,5	10	
	4300—	430—							
	1000—	100—							
Ferrous metals	4300—	430—	$P=30D^2$	Below 3	2,5	1 875	187,5	30	
	to 1000	to 100							
	to 1000	to 100							
	to 1000	to 100							
Nonferrous metals: brass	310—	31—	$P=10D^2$	Below 6	10	10 000	1000	30	
	1300—	130—							
	310—	31—		6—3	5	2 500	250	30	
Aluminum and magnesium alloys	310—	31—	$P=10D^2$	Above 3	2,5	625	62,5	30	
	1300—	130—							
Aluminum Nonferrous metals Bearing alloys	80—350	8—35	$P=2,5D^2$	Below 6	10	2 500	250	60	
	80—350	8—35		3—3	5	625	62,5	60	
	80—350	8—35		Above 3	2,5	156	15,6	60	

In Fig. 2.7 is given diagram of Brinell press with electric motor.

For determination of hardness tested sample is mounted on stand 1. Wheel 2 is rotated, raising table until preload is created. Achievement of preload is monitored in accordance with contact of moving graduation line with stationary line. Then by depressing push button motor 5 is started.

Motor frees lever supporting balance arm with weights 3. Weights are lowered, and through level system load is transmitted to ball 4, pressed into tested metal.

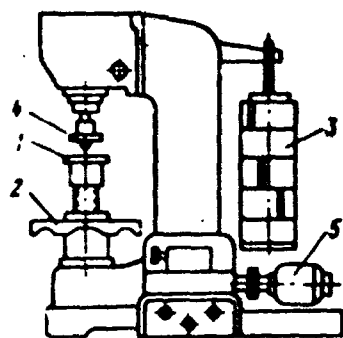


Fig. 2.7. Brinell press.

Holding under load usually is equal to 10-60 sec, depending on hardness of investigated metal. Load is removed automatically with help of motor. After automatic shutoff of motor, by turn of wheel 2 counterclockwise stand is lowered and sample is removed.

HB is determined from measured diameter of imprint by using special tables.

Mean values of hardness of certain metals and alloys are: for aluminum HB = 200 MN/m² (20 kgf/mm²), for iron HB = 800 MN/m² (80 kgf/mm²), for annealed medium-carbon steel HB = 1800 MN/m² (180 kgf/mm²).

Between Brinell hardness and ultimate tensile strength for different materials are defined dependencies, established by experimental means:

- for carbon steel $\sigma_B = 0.36 \text{ HB}$;
- for Cromansil steel $\sigma_B = 0.35 \text{ HB}$;
- for chromium and chromium-nickel steels $\sigma_B = 0.34 \text{ HB}$;
- for chromium-molybdenum steels $\sigma_B = 0.33 \text{ HB}$;
- for Duralumin $\sigma_B = 0.37 \text{ HB}$;
- for brass $\sigma_B = 0.53 \text{ HB}$;
- for pure copper $\sigma_B = 0.48 \text{ HB}$;
- for pure nickel $\sigma_B = 0.57 \text{ HB}$.

Basic deficiencies of determination of hardness by this method are the following:

1. Impossibility of determination of hardness of materials with HB of more than 4500 MN/m² (450 kgf/mm²), owing to deformation of ball and distortion of imprint.
2. Limited applicability of this method to parts of complicated configuration.
3. Impossibility of testing thin-sheet or surface-hardened material.

4. Damage of surface of tested material due to obtaining of large imprints.
5. Comparatively long time required for determination of hardness.

Measurement of hardness by Rockwell method. For test by Rockwell method into tested metal is pressed a diamond cone or steel ball and from depth of obtained imprint is determined hardness. For test of materials of low and medium hardness [$HB < 2000 \text{ MN/m}^2$ (200 kgf/mm^2)] is applied steel ball with diameter of 1.59 mm (1/16") under load of 100 kgf (scale B, red): designation of hardness HRB. Scale B is used for tests of nonferrous metals and nonhardened steels. For test of hard materials [$HB > 2000 \text{ MN/m}^2$ (200 kgf/mm^2)] is applied diamond cone with vertex angle of 120° under load of 150 kgf (scale C, black) or 60 kgf (scale A, black). Designations of hardness are respectively HRC and HRA. Scale C is used for hardened steels, scale A for hard alloys.

In both cases load is applied consecutively in two passes — first a preload of 10 kgf and then the main load, equal in combination with preload to 60, 100, and 150 kgf.

Measure of Rockwell hardness is a value that is the reciprocal of difference of depth of penetration of diamond cone or steel ball under action of main and preliminary loads. Hardness number is expressed in conditional dimensionless units.

Measurement of hardness is produced on press of Rockwell type (Fig. 2.8) on lower part of stationary bed of which is Table 1 for tested sample. On upper part of bed are mounted indicator 4, oil regulator to provide smoothness of load 5, and rod 6, in which is established tip with diamond cone or with steel ball of 1.59 mm diameter. Indicator 4 constitutes instrument on dial of which are two scales (black and red), and there are two pointers: large indicates hardness and small is for monitoring magnitude of preload.

Work on instrument is carried out as follows: wheel is turned to raise table until small pointer is aligned with red dot on dial. This signifies that tip has pressed into sample under action of preload. Such load is necessary for guarantee of tight contact between tip and sample and also for removal of gaps capable of influencing results of test.

After this, by turning scale of indicator figure 0 (zero) is aligned on black scale of dial (or figure 30 on red scale) with large pointer. Then with light pressure crank 7 is freed and it shifts smoothly to stop. Such shift of crank

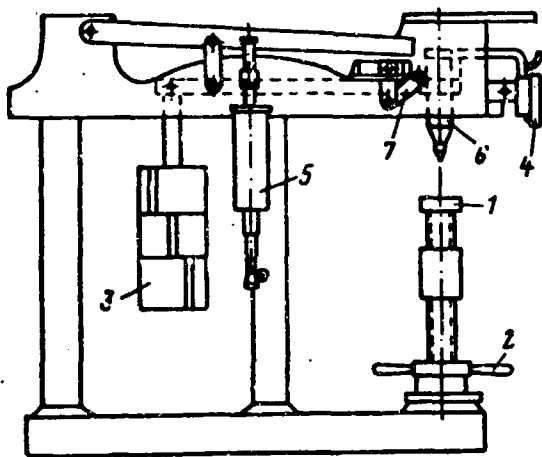


Fig. 2.8. Press of Rockwell type.
1 - table, 2 - wheel, 3 - weight,
4 - indicator, 5 - oil regulator,
6 - rod, 7 - crank.

transmits main load to tested sample through system of levers.

Loading is produced until lever system stops. Then crank 7 smoothly shifts upward, thereby removing main load but leaving preload. Figure indicated by large pointer on scale of dial represents Rockwell hardness number. After this by turning wheel counterclockwise table is lowered with sample, thereby removing preload.

Distance from center of imprint to edge of sample or to center of other imprint

should be not less than 2.5 mm with cone and not less than 4 mm with ball.

Thickness of sample should be not less than 0.8 mm with diamond cone and not less than 1.5 mm with ball. Measurement of hardness, especially by diamond cone, should be made no less than three times on one sample with determination of average result.

Divergence between values of hardness of up to three units is allowed.

Measurement of Rockwell hardness has following advantage over measurement of hardness per Brinell:

1. For determination of hardness is required less time (30-60 sec).
2. Measurement of hardness leaves smaller imprint on surface of part.
3. There is possibility of determination of hardness of comparatively thin samples (to 0.8 mm).
4. Application of diamond cone permits one to determine hardness of hard materials [$HB > 4500 \text{ MN/m}^2$ (450 kgf/mm^2)].

If it is required to measure hardness of layer of metal of thickness less than 0.3 mm by diamond cone under load of 60 kgf, analogous instruments are applied, but with smaller load (45, 30, and 15 kgf) and less depth of penetration (every scale division equal to depth of 0.001 mm).

There exists dependence between Brinell and Rockwell hardness. This dependence is given in Table 3.

Measurement of hardness by Vickers method. Determination of hardness by

Table 3. Relationship Between Brinell and Rockwell Hardness

Brinell hardness 10/3000		Rockwell hardness			
		diamond tip		steel ball 1/16"	
diameter of im- print, mm	hardness number HB MN/m ²	scale A, load 60 kgf	scale C, load 150 kgf	scale F, load 60 kgf	scale B, load 100 kgf
2,40	6590	83,0	6,3	—	—
2,45	6270	82,0	61,0	—	—
2,50	6010	81,0	59,0	—	—
2,55	5800	80,0	58,0	—	—
2,60	5550	79,0	56,0	—	—
2,65	5340	78,5	54,0	—	—
2,70	5140	78,0	52,5	—	—
2,75	4950	76,0	51,0	—	—
2,80	4770	76,0	49,0	—	—
2,85	4610	75,0	48,0	—	—
2,90	4440	74,0	47,0	—	—
2,95	4290	73,0	45,0	—	—
3,00	4150	73,0	44,0	—	—
3,10	3880	71,0	41,0	—	—
3,20	3630	70,0	39,0	—	—
3,30	3410	69,0	37,0	—	—
3,40	3210	68,0	35,0	—	—
3,50	3020	67,0	33,0	—	—
3,60	2850	66,0	30,0	—	—
3,70	2690	65,0	28,0	—	—
3,80	2550	64,0	26,0	—	—
3,90	2410	63,0	24,0	114,0	100,0
4,00	2290	62,0	22,0	112,5	98,0
4,10	2170	61,0	20,0	111,5	97,0
4,20	2070	60,0	18,0	110,5	95,0
4,30	1970	58,0	—	110,0	93,0
4,40	1870	57,0	—	—	91,0
4,50	1780	56,0	—	108,0	89,0
4,60	1700	55,0	—	107,0	86,0

Vickers method is based on pressing into tested material of tetrahedral diamond pyramid under action of defined load with subsequent measurement of diagonals of imprint with the help of microscope (Fig. 2.9).

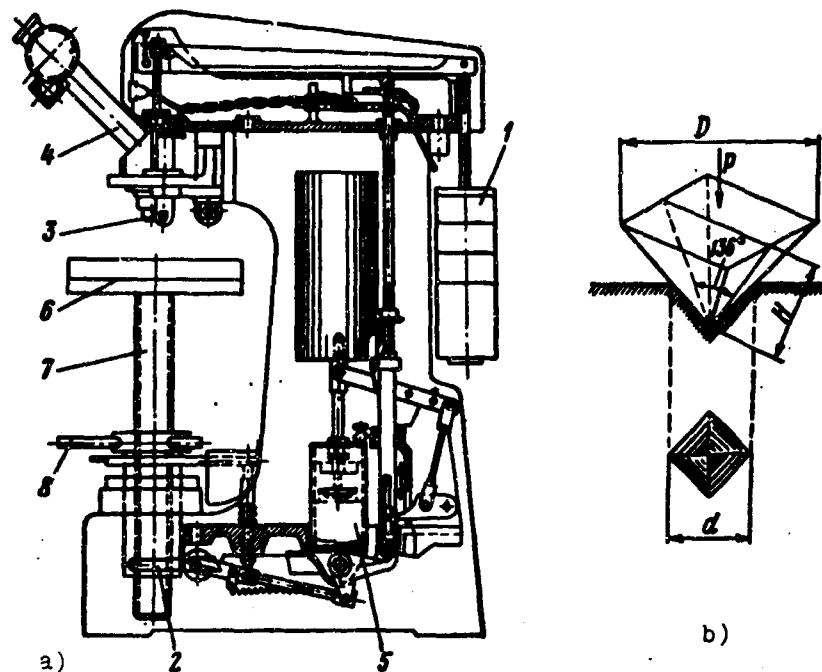


Fig. 2.9. Determination of Vickers hardness. a) general view of instrument. 1 - removable weights, 2 - crank, 3 - diamond pyramid, 4 - microscope, 5 - oil regulator, 6 - table, 7 - screw, 8 - wheel. b) measurement of imprint.

Vickers hardness HV is expressed by ratio of load P to surface of pyramidal imprint F, i.e.,

$$HV = \frac{P}{F} = \frac{2P \sin 68^\circ}{d^2} [N/m^2 (kgf/mm^2)].$$

Diamond pyramid has interface angle of 136° . Magnitude of load during Vickers test may be from 5 to 120 kgf and must be specified in records of test. Most frequently applied is load 5 or 10 kgf.

Samples for Vickers hardness test must have polished surface. Thickness of sample should be not less than 1.5 times diagonal of imprint.

Vickers method is especially convenient for measurement of hardness of surface-hardened parts having complicated configuration (for instance, nitrated and carbonitrated teeth of gears, etc.).

Hardness numbers HV to 400 units coincide with HB hardness numbers. For hardness of more than 400 Vickers numbers exceed Brinell numbers, and this by more the higher the hardness.

Measurement of microhardness. In a number of cases it is necessary to determine hardness of sections of material very small in area or thickness. For instance, hardness of light-gage sheet, thin surface layers, and separate structural components.

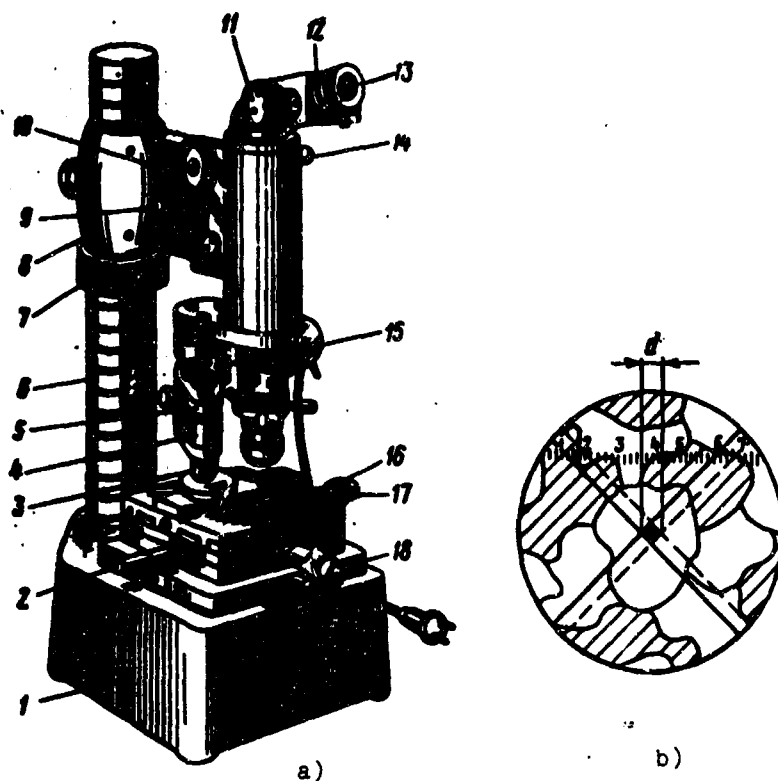


Fig. 2.10. Instrument for measurement of microhardness. a) general view of instrument. 1 - base, 2 - handle, 3 - mounting with diamond tip, 4 - weights, 5 - load mechanism, 6 - column, 7 - nut, 8 - bracket with sleeve, 9 - microfeed screw, 10 - coarse adjustment, 11 - micrometer drum, 12 - ocular micrometer, 13 - eyepiece, 14 - micrometer mounting screw, 15 - stop, 16 - stage, 17, 18 - micrometric screws; b) measuring imprint.

For solution of such problems, for determination of microhardness it is very convenient to apply Khrushchov-Berkovich method. In Fig. 2.10 is shown instrument [PMT-3] (ПМТ-3) for test of metals for microhardness. Principle of action of this instrument is based on indentation under loads of from 2 to 200 gf of diamond tetrahedral pyramid and subsequent measurement of imprint with help of microscope. Using table, from length of diagonal of imprint we find value of hardness.

Surface of tested sample should be buffed and work hardening on surface of sample removed by etching.

Impact Test

Ability of material to sustain dynamic loads is checked by impact test. Material is subjected here to deformation at high speed, by which its inclination to brittle fracture is revealed.

Impact test is applied basically to structural steel. Brittle materials (cast iron) or materials possessing great ductility (brass) are not suited to impact testing.

For impact test are applied special samples with notch, destruction of which is produced on special pendular drivers (Fig. 2.11a, b). Dimension of sample is $10 \times 10 \times 55$ mm.

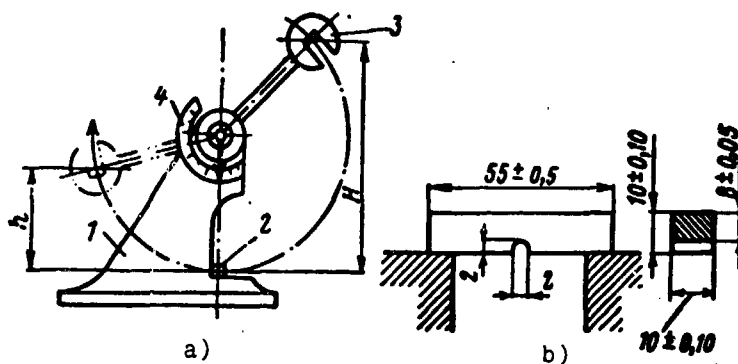


Fig. 2.11. Pendular driver. a) diagram of driver, b) sample for impact test. 1 - bed, 2 - sample, 3 - driver, 4 - scale.

Before test pendulum rises upwards by angle α and is secured by latch. Sample is placed on supports of driver with notch facing opposite blow of striker. Then pendulum is released and, dropping, destroys sample. After blow pendulum swings to other side of vertical axis by certain angle β , magnitude of which is fixed by scale pointer.

Impact toughness a_H , i.e., work of impact fracture, referred to cross section of sample at place of notch, is determined by the formula

$$a_H = \frac{A_H}{F_0} [J/m^2 (kgf/cm^2)],$$

where A_H - work of blow expended on destruction of sample, in Joules; F_0 - area

of cross section of sample in place of notch, in m^2 ;

$$1 \text{ kgf-m/cm}^2 = 10^5 \text{ J/m}^2 = 0.1 \text{ MJ/m}^2.$$

Different materials possess various impact toughness. Thus, for instance, low-carbon steel has $a_H = 0.4-0.8 \text{ MJ/m}^2$ ($4-8 \text{ kgf-m/cm}^2$), and alloy steel $1.0-1.8 \text{ MJ/m}^2$ ($10-18 \text{ kgf-m/cm}^2$).

Besides appraisal of numerical values obtained during impact test, an important criterion of quality of metal is fracture of samples. Fibrous dull fracture without characteristic metallic luster testifies to ductile fracture. Brittle fracture gives lustrous crystalline fracture.

Endurance Test

Static and impact tests are insufficient for study of strength of metals subjected to action of repeatedly-varying and sign-alternating stresses.

Machine parts in which appears large number of repeated alternating stresses sometimes are subject to sudden and brittle fracture, occurring during stresses lying considerably below ultimate strength. Destruction of metals as a result of action of such stresses is called phenomenon of fatigue.

For fatigue breakdown is characteristic special form of break, consisting of two zones (Fig. 2.12): smooth lustrous zone of fatigue 1 and zone of brittle fracture with coarse crystalline structure 2.

In practice of exploitation of aviation materiel it is necessary to deal with many parts subject to fatigue breakdown. Such include: blades of gas turbine, crankshafts, aircraft longerons, chassis components, etc.

Test for determination of strength during alternating stresses is called endurance or fatigue test.

Fig. 2.12. Break of metal destroyed from fatigue.

Such tests determine number of changes of loads (number of cycles which sample sustains before destruction under given stresses.

Endurance test is made on special machine in which rotatable sample is subjected to influence of buckling loads (Fig. 2.13).

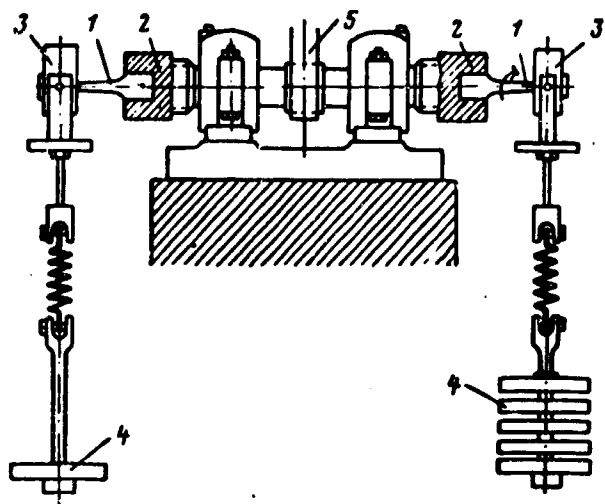


Fig. 2.13. Machine for endurance test.
1 - samples, 2 - chucks, 3 - bearings,
4 - weights, 5 - drive belt.

Results of test are recorded in the form of diagram called an endurance curve. On vertical axis are plotted stresses σ , under which samples are tested. On horizontal axis is plotted quantity of cycles N . On endurance curve is determined the biggest stress under which sample is able to sustain any number of changes of loads without destruction. This stress is called endurance or fatigue limit and is designated σ_{-1} . Endurance curve, plotted

on coordinates σ - N (Fig. 2.14a), does not have sharp transition to horizontal section, which hampers possibility of exact determination of endurance limit. Therefore it is more convenient to use method of plotting endurance diagram on logarithmic coordinates (Fig. 2.14b), for which this transition is more clearly expressed.

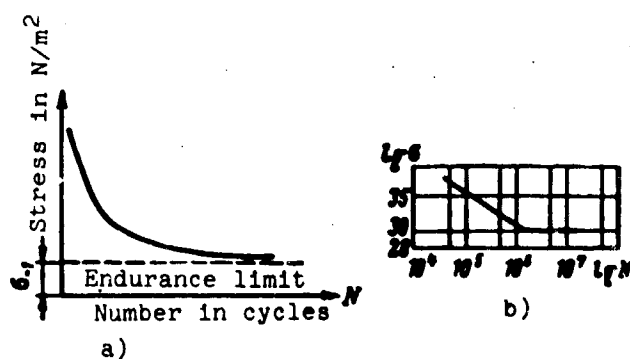


Fig. 2.14. Endurance curves. a) in usual coordinates, b) in logarithmic coordinates.

For determination of endurance limit it is sufficient to bring number of cycles to 5 million during test of steel and to 20 million during test of light and heat-resisting alloys. Samples of these materials sustaining shown quantity of cycles without break serve satisfactorily during large number of changes of load also; therefore they are considered suitable for manufacture of corresponding parts. In practice the endurance limit of steel is 35-50% of ultimate strength established

by usual tensile test.

Endurance limit depends on a series of factors: degree of contamination of metal by nonmetallic inclusions, state of surface, structure of metal, form of part, and others.

Endurance limit is increased by means of hardening surface and creation in external layers of metal of compressing stresses (by shot-blasting, nitration, carburizing, etc.).

Existing methods of testing metals for fatigue are distinguished by type of applied load and by conditions of carrying out experiment. Tests are conducted under bend, torsion, extension - compression, at high and low temperatures, in corrosive media, etc.

§ 3. Tests at High Temperatures

Work of majority of parts and assemblies of contemporary airplane constructions occurs under conditions of joint prolonged action of loads and heating.

Therefore in aviation technology of tremendous value are mechanical properties which materials have at high temperatures. High temperatures for given material is considered that composing not less than $0.5 T_{\text{пл}}$ [meeting point] on absolute scale. Thus, high temperatures for steels are those over 600°C , and for aluminum and magnesium alloys those over 150°C .

Behavior of metals and alloys during prolonged high-temperature loading differs from their behavior at usual temperatures.

Characteristics of strength and ductility of majority of technical alloys at usual temperatures in practice do not change with time. And under action of high temperatures and loads in them occurs considerable change of mechanical properties with time. With increase of duration of loading, characteristics of strength and ductility worsen.

Since change of strength may differ with duration of test, for appraisal of exploitational properties of alloys under high-temperature loading it is necessary to consider character of change of their strength characteristics with time.

In Fig. 2.15 are given curves of change of ultimate strength of two alloys, depending upon duration of test. Ultimate strength of first alloy $\sigma_{\text{в1}}$ during small duration of test is less than ultimate strength of second alloy $\sigma_{\text{в2}}$. However, for parts working at high temperatures for prolonged time it is more profitable to use first alloy, since strength of second alloy strongly worsens with increase of duration

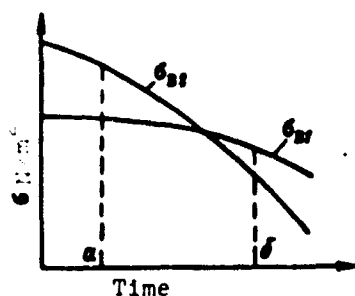


Fig. 2.15. Change of strength of two alloys in dependence upon duration of test.

of test. And after duration of test σ ultimate strength of first alloy will be already greater than ultimate strength of second alloy.

At present in order to obtain reliable data about behavior of materials at high temperatures and under permanent loads, they are subjected to special mechanical tests.

Brief Tensile Tests

Tensile tests at high temperature are produced under ordinary static loading, when load increases during short interval of time calculated in minutes.

Brief tests do not characterize in full measure the properties of metals and alloys at high temperatures. On the basis of brief tests there can be obtained an idea about behavior of material of parts in initial period of their work.

For brief tests are used ordinary machines applied for static tests, supplied with heating devices (Fig. 2.16).

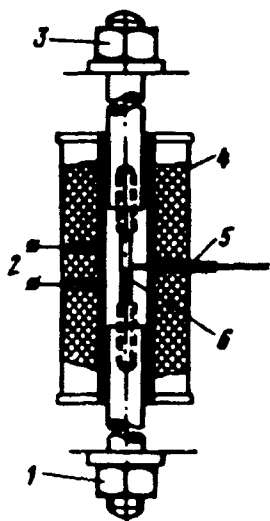


Fig. 2.16. Diagram of tensile test at high temperatures. 1, 3 - clamps of machine, 2 - feed of current, 4 - furnace, 5 - thermocouple, 6 - sample.

Creep Tests

If at high temperature metal is loaded by constant stress lower than yield point at some temperature and left under load for sufficiently prolonged time, material during entire time of action of temperature and load will be deformed at certain speed. Such phenomenon is called creep. For steel creep is observed at temperatures over 350°C .

Basic form of creep test is that made under conditions of extension. In Fig. 2.17 is depicted diagram of machine for creep test. Sample for creep test is subjected to action of standed load at the same temperature, and after assigned intervals of time elongation of sample is determined. Results of test are compiled in the form of graph, called creep curve. Plotting creep curve is produced on coordinates "elongation per unit length - time" (Fig. 2.18).

Segment 0-1 characterizes elastic elongations, which form immediately after

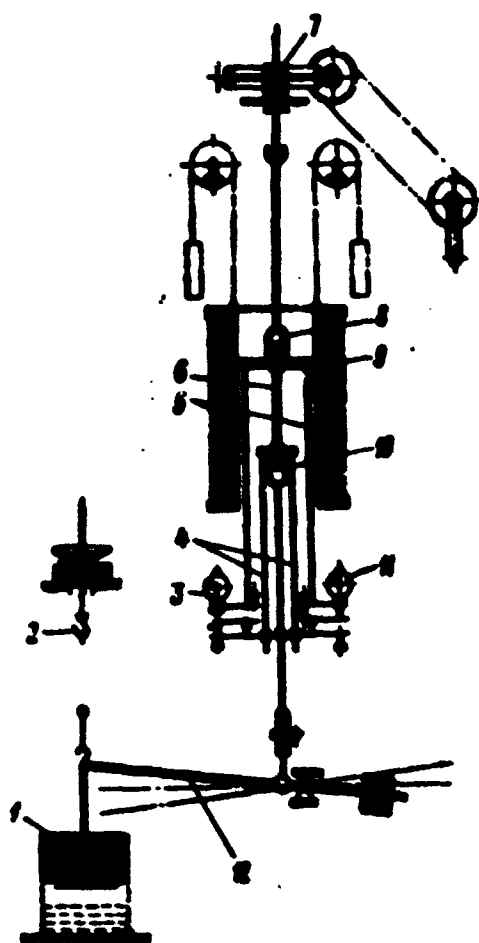


Fig. 2.17. Diagram of machine for creep test. 1 - weights, 2 - damper, 3, 11 - indicator, 4, 5 - rods, 6 - sample, 7 - loading mechanism, 8 - upper clamp, 9 - furnace, 10 - lower clamp, 12 - lever.

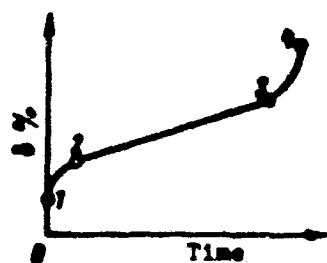


Fig. 2.18. Characteristic curve of creep.

loading of sample. Section of curve 1-2 is called period of transient creep, during which deformation takes place with nonuniform, decreasing speed. Section of curve 2-3 is called period of steady-state creep taking place with constant speed of deformation. Section 3-4 is characterized by sharp growth of creep, terminating with destruction of sample.

In Fig. 2.19 are presented creep curves for the same material, tested at the same temperature under different stresses. The less the stress the less the speed of creep and the longer the sample will sustain load without destruction. With increase of stress, curve is steeper, speed of creep increases, and destruction of sample occurs.

In the same manner is changed character of creep curves of material under the same stress but at different (increasing) temperatures.

Creep limit is characteristic of resistance of metal to small plastic deformations.

Creep limit is stress which causes, after defined interval of time at given temperature, given total elongation or speed of deformation.

Creep limit designated by sign of stress with two indices. Thus, for example, $\sigma_{0.1/300} = 250 \text{ MN/m}^2$ (25 kgf/mm^2) signifies that at given temperature, for instance at 800°C , stress equal to 250 MN/m^2 (25 kgf/mm^2) for 300 hours of tests causes elongation of sample of 0.1%.

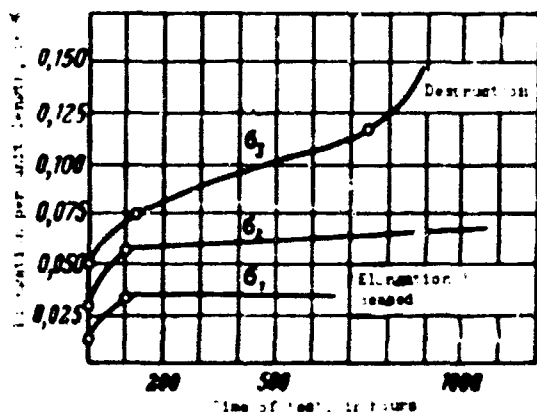


Fig. 2.19. Variation of creep with time of test for different stresses and constant temperature.

For different parts magnitude of allowance for deformation varies from 0.1 to 1% and duration of test varies from 100 to 500 hours.

Value of creep limit for the same material depends on duration and temperature of test and on allowance for deformation. With decrease of duration of test and constant allowance for deformation, value of creep limit is increased. With decrease of permissible deformation, other conditions being equal, magnitude of creep limit

also decreases. An especially considerable decrease of creep limit under these conditions occurs with increase of temperature of test.

Tests for Stress-Rupture Strength.

Important property of alloy working at high temperatures is its ability to resist destruction under prolonged affect of loads. This property is called stress-rupture strength.

It is possible to produce tests for stress-rupture strength on the same machines used for creep tests, but they must have attachments for damping of blow of weights, snapping at the time of rupture, and for fixation of time of rupture of sample. Samples are tested under constant loads and temperature to destruction.

Tests for stress-rupture strength are more accelerated than tests for creep, since here are applied higher loads, provoking considerably greater deformations.

Most frequently tests for stress-rupture strength are continued for 100, 200, or 300 hours, and results of tests are depicted graphically on coordinates "stress - time to rupture" (Fig. 2.20).

Characteristic of resistance of metal to destruction at high temperatures is stress-rupture strength.

Stress-rupture strength is stress which causes destruction of sample at given temperature in defined interval of time.

For designation of stress-rupture strength is used the following notation:
 $\sigma_{300} = 150 \text{ MN/m}^2$ (15 kgf/mm^2). This signifies that at given temperatures, for

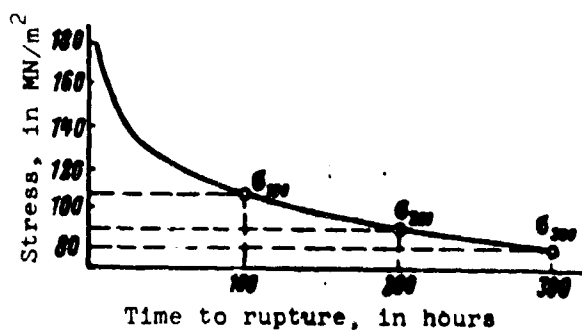


Fig. 2.20. Curve of stress-rupture strength.

instance at 800°C, stress equal to 150 MN/m² (15 kgf/mm²) causes destruction of alloy after 300 hours.

Numerical values of stress-rupture strength and creep limit obtained under the same conditions of test for the same material do not coincide.

Value of stress-rupture strength for the same material depends on duration and temperature of test. The greater the duration and temperature of test, the less the value of stress-rupture strength for the same material. Obviously at given temperature metal can serve longer under smaller stress.

Endurance Tests

Of essential value for period of service of parts at high temperatures is ability of material to resist to destruction during action of repeatedly-varying loads, i.e., during work to fatigue.

Standard tests for endurance at high temperatures are produced by repeatedly-varying bending. For these tests are used ordinary machines supplied with heating devices.

In process of testing for endurance at high temperatures on endurance curve no horizontal section is obtained, which is characteristic for normal temperatures of test, i.e., during high-temperature tests for endurance stress bringing about failure continuously decreases with increase of number of cycles to very large values.

Endurance limit at assigned temperature is the biggest stress which sample sustains assigned number of cycles without destruction.

For determination of endurance limit at high temperatures as base are taken $5 \cdot 10^6$; $10 \cdot 10^6$; $50 \cdot 10^6$, and $100 \cdot 10^6$ cycles.

Hardness Tests

For determination of hardness at high temperatures or so-called "hot" hardness there chiefly are applied methods of indentation.

For this can be used any press supplied with heating attachment (Fig. 2.21).

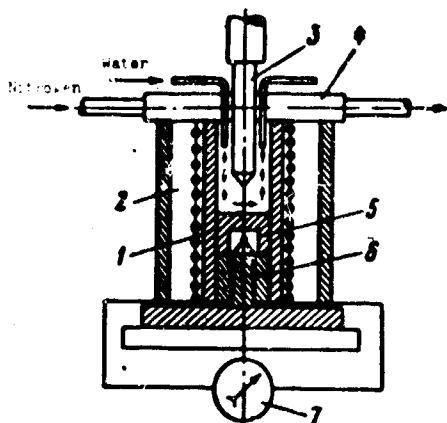


Fig. 2.21. Instrument for determination of hardness at high temperatures. 1 - porcelain cylinder, 2 - furnace, 3 - punch, 4 - cover, 5 - sample, 6 - thermocouple, 7 - galvanometer.

Sample having recess at bottom for introduction of thermocouple is established in electric oven heated to assigned test temperature.

During test a ball of 5 or 10 mm diameter is pressed under constant load into test sample, heated to assigned temperature. Measure of "hot" hardness is ratio of load to surface of obtained imprint. Ball is prepared from alloy steel or heat-resistant alloy.

The most important factor of "hot" hardness is time. With increase of duration of test, hardness drops.

§ 4. Technological Tests

Technological tests are for the purpose of determining fitness of material for particular technological processes. Results of technological tests are judged from state of surface after test. Sample is considered as having sustained test if on its surface after test are revealed no cracks, rents, stratification, or fracture. Methods of carrying out technological tests are specified by corresponding GOST's and OST's.

The most widely applied technological tests are flanging, fluxure, extrusion, and wire coiling.

Flanging is carried out for determination of ability of metal to take bend of given dimensions and form. It is conducted both in cold and heated states, depending upon form of material and its assignment. Flanging test is conducted differently; to defined angle, to parallelism of sides, to full contact (Fig. 2.22).

This test is applied to sheet and strip materials with high plasticity intended for cold or hot pressure working.

For production of flanging test are applied presses or vice.

Fluxure test serves for determination of ability of metal to sustain repeated bending and unbending (Fig. 2.23). For test sheet material sample of defined dimensions is selected, which is clamped in jaws of instrument in vertical position. During test sample is bent and unbent in plane perpendicular to tangent of jaws of

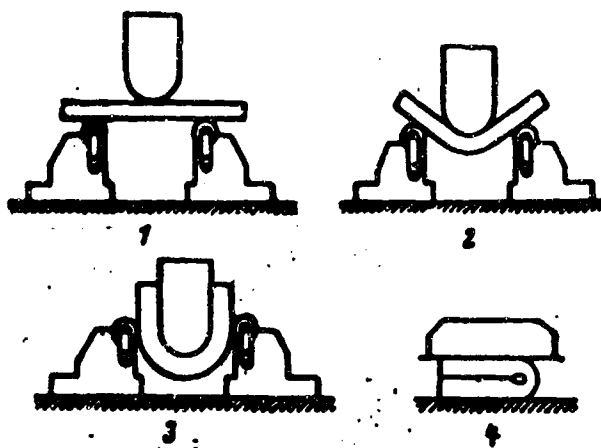


Fig. 2.22. Flanging test of metal. 1 - position before test, 2 - test to determined angle, 3 - test to parallelism of sides, 4 - test to full contact of sides.

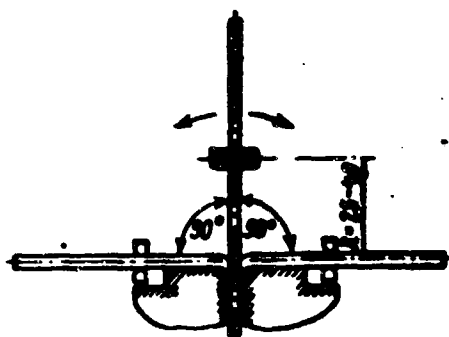


Fig. 2.23. Flexure test.

instrument. Bending is done alternately 90° to both sides at speed of up to 60 bends per minute. One cycle is composed of bending and unbending 90° to each side. Flexure test is conducted in cold state. To test are subjected sheet materials and wire.

Extrusion test is used for determination of ability of sheet metal to be subjected to stamping and drawing. For carrying out of test from sheet is cut sample, which is placed in special instrument (Fig. 2.24). This instrument consists of punch, of die, and clamp. During test sample is forced against die, and then by slow rotation of wheel there is forced into it the hardened, polished spherical element of working part of stamp (punch). Punch is pressed in until crack appears, which is detected by mirror. Plasticity of metal is judged from depth of drawing of sample to moment of appearance of crack.

Test for coiling of wire is applied only for test of wire of diameter up to 6 mm and serves for appraisal of ability to take assigned coiling (resile properties). Wire is coiled on cylindrical rod of defined diameter to defined quantity of turns (Fig. 2.25). After test, in material of sample and also in coverings must be revealed no stratifications, cracks, exfoliation, rents, breaks, etc.

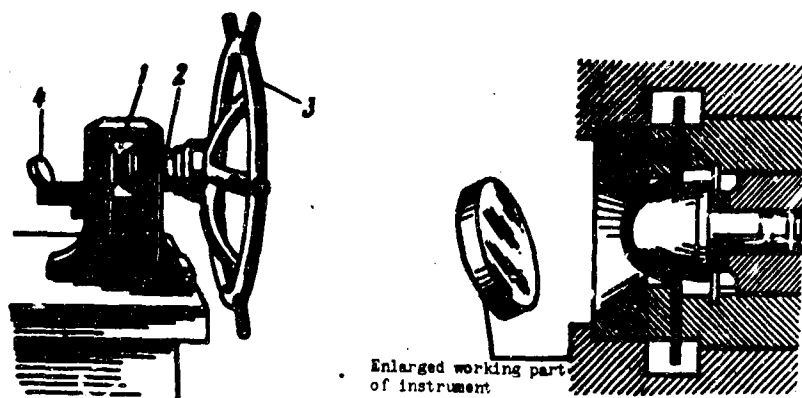


Fig. 2.24. Extrusion test of material. 1 - slot; 2 - screw; 3 - wheel, 4 - mirror.

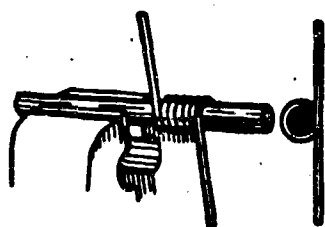


Fig. 2.25. Coiling test of wire.



Fig. 2.26. Test of tubes for bend.

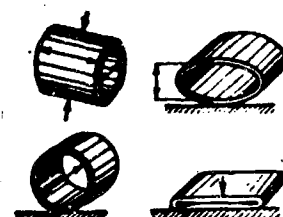


Fig. 2.27. Test of tubes for flattening.

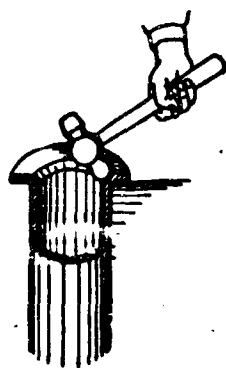


Fig. 2.28. Test of tubes for flattening.

Tests of tubes. Tubes are tested for bend (Fig. 2.26), for flattening (Fig. 2.27), and for beading (Fig. 2.28).

These tests serve for determination of ability of pipes to sustain different form of change of their form.

Foundry tests. During foundry tests, for determination of fluidity molten sample of metal is poured into channel molded in earth, having form of spiral. Measure of fluidity is length of flooded part of spiral.

CHAPTER III

METHODS OF INVESTIGATION OF METALS AND ALLOYS

For study of structure of metals and alloys are applied various methods of investigation: chemical analysis, metallographic analysis, X-ray diffraction analysis, and thermal analysis. First method is used for determination of composition of alloy or establishment of purity of metal. The following two are used for study of structure and last for study of transformations which occur in metals and alloys with changes of temperature.

§ 1. Analysis of Chemical Composition

Chemical analysis permits one to determine content of elements entering in composition of some or another alloy and also to establish degree of contamination of pure metals by other elements. Chemical analysis is divided into qualitative and quantitative. Qualitative analysis permits one to determine what elements, and sometimes compounds, are in metal or alloy and their comparative quantities (much, little, or traces). Quantitative analysis permits one to determine exactly quantities by weight of elements in chemical compounds entering in composition of metal and alloy.

Spectral analysis of metals and alloys, in comparison with chemical analysis, has advantages, thanks to high sensitivity, accuracy, speed of carrying out, and cheapness. For carrying out of spectral analysis there are needed in all a few milligrams of investigated substance, which permits analyzing thin wires, metallic coverings, etc.

Spectral analysis is based on study of spectrum of metals and alloys. Heated

vapors of every metal have their own defined spectrum. This spectrum completely characterizes every element and helps one to detect it unerringly. Spectra of alloys constitute spectra of simple elements. This is why, depending upon defined lines of spectrum, it is possible to judge qualitative composition of alloy.

Brightness and intensity of spectral lines of separate elements entering in composition of alloy is changed in dependence upon their content in given alloy. Comparing intensity of spectral lines of separate elements, one can determine tentatively their percentage in given alloy.

§ 2. Structural Analysis

Structural analysis includes investigation of macrostructure, microstructure, and atomic structure (X-ray structure).

Macroanalysis is study of structure of metals and alloys with unaided eye or under slight magnification. Macrostructure can be studied directly on surface of metal (for example, a casting), in fracture of a part, or most frequently after preparation of investigated surface, consisting in grinding and etching.

On etched surface one can detect orientation of crystals in metal, presence of cracks, quality of weld seam, etc. In cast steel is revealed orientation of dendrites; in rolled or forged steel is seen fibrous structure of deformed crystals.

Macroanalysis allows one also to see distribution in steel such harmful impurities as sulfur and phosphorus.

In Fig. 3.1 is represented macrostructure of a cast blade of nozzle apparatus of gas turbine, and in Fig. 3.2 is shown macrostructure of a stamped valve.

Microanalysis is the study of structure of metals and alloys with the help of metallographic microscope.

Microanalysis as method of investigation of metals and alloys was first applied in 1831 by P. P. Anosov for study of patterns of appearing on surface of polished steel after etching it in acid.

At present microanalysis is one from basic methods of investigation of structure of metals and alloys, checking quality of metal, and studying causes of destruction of parts in exploitation.

For carrying out of microanalysis it is necessary to prepare microsection - sample with surface prepared for investigation. For manifestation of microstructure ground and then polished surface is etched in special chemical reagents, whose



Fig. 3.1. Macrostructure of cast blade of nozzle assembly of gas turbine.

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Fig. 3.2. Macrostructure of stamped valve.

composition includes acid, salt, or alkali.

Reagent corrodes surface, giving it greater relief.

Besides this, it colors different structural com-

ponents of alloy differently. This purpose is

served by electrolytic polishing of metals. In

Fig. 3.3 is given diagram explaining visibility of

grain boundaries under microscope a and

microstructure of metal with clear outline of

grain boundaries b.

Microanalysis allows one:

a) to determine structure of alloy and also

dimensions and form of separate grains and on this

basis to make conclusion concerning character of casting, degree of deformation during cold pressure treatment, and conditions of heat treatment;

b) to detect different flaws of metals and alloys, as, for example, nonmetallic inclusions, micropores, microcracks, traces of oxidation, overheating, overburning, etc.;

c) to detect composition of structural components;

d) to measure depth of penetration and to determine character of corrosion of parts.

For study of microstructure are applied metallographic microscopes (Fig. 3.4).

Diagram of optical system of metallographic microscope is shown in Fig. 3.5. Beam from source of light 1 strikes prism 2 of microscope and, being refracted in prism, goes to objective 3. Above objective is located slide 4. Beam of light is reflected from slide and through objective heads through prism 5 to eyepiece 6.

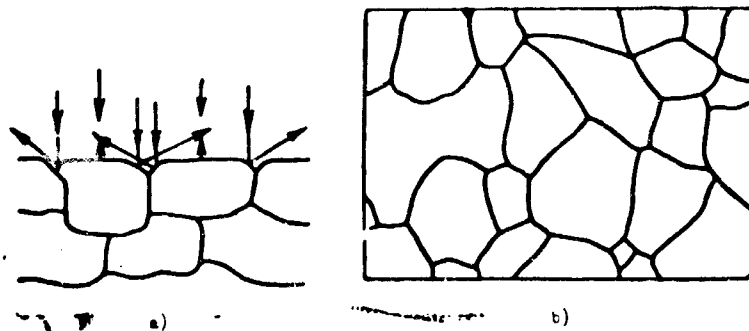


Fig. 3.3. Diagram of reflection of beams and manifestation of microstructure of metal.

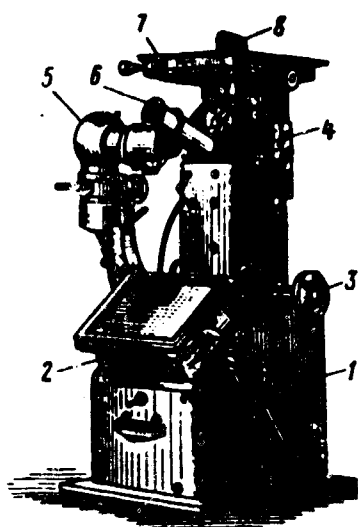


Fig. 3.4. Metallographic microscope. 1 - body, 2 - camera, 3 - screw for rough focusing, 4 - micrometric screw, 5 - illuminator, 6 - eyepiece, 7 - stage, 8 - microsection.

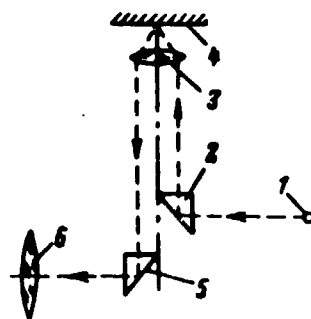


Fig. 3.5. Diagram of path of beams of metallographic microscope. 1 - source of light, 2 - prism, 3 - objective, 4 - microsection, 5 - prism, 6 - eyepiece.

Microstudy by optical microscope permits one to detect particles with minimum dimensions to 2 microns (μ): $1 \mu = 1 \cdot 10^{-6}$ m. Magnification applied is from several tens to 2000 times.

At present electron microscopes are finding ever wider application. Or electron microscope created in USSR study of microstructure is produced during magnification of up to 100,000 times, which permits observation of particles to 0.0003μ . In Fig. 3.6 is presented diagram of electron microscope. In Fig. 3.7 is shown structure of steel as seen by optical and electron microscope.

X-ray diffraction analysis. X-ray diffraction analysis is important method of investigation of structure of materials. It is based on ability of X-rays to penetrate solids to one degree or another. X-rays are electromagnetic oscillations with small wavelength, commensurate with parameters of crystal lattices of metals.

X-ray diffraction analysis allows one to establish types of crystal lattices of metals and alloys and their parameters. Definition of structure of metals and

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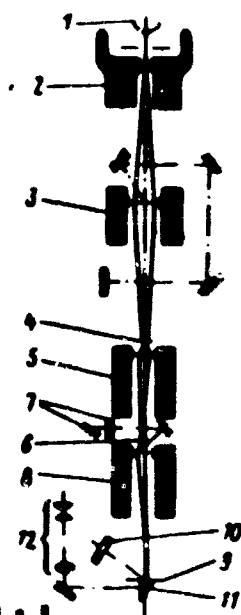


Fig. 3.6. Diagram of electron microscope. 1 - cathode, 2 - anode, 3 - condenser (electromagnetic lens), 4 - object, 5 - objective lens, 6 - fluorescent screen, 7 - viewing hatch, 8 - projection lens, 9 - fluorescent screen, 10 - viewing hatch, 11 - prism, 12 - optical microscope.



Fig. 3.7. Microstructure of steel. a) revealed by optical microscope ($\times 1000$); b) revealed by electron microscope ($\times 15,000$).

which on film is obtained series of bands whose position and intensity depend on type of crystal lattice of material of sample. Deciphering thus obtained X-ray photograph, one can determine type and parameter of space lattice.

In recent years in metal science there has found wide application the method of radioactive isotopes (method of "tagged atoms").

This method is based on fact that tagged atoms introduced into alloy in the form of radioactive isotopes can be detected with the help of radiography or by other method. Tagged atoms introduced into alloy behave identically as ordinary atoms during different processes occurring in alloy. This enables one to study many physical and chemical processes occurring in alloys. Thus, method of radioactive isotopes permits one to investigate distribution in alloys of alloying

elements. Distance between them is based on reflection of X-rays by atomic planes of crystal lattice. Knowing wavelength of X-rays, one can determine distance between atomic planes (and separate atoms) and diagram (system) of location of atoms in space.

With X-ray diffraction analysis it is possible to investigate both separate crystals also metal or alloy in the form of fine powder.

In Fig. 3.8 is shown diagram of X-ray diffraction analysis. X-ray beam, striking investigated sample, is reflected from certain atomic planes and, combining, strikes film contained inside special chamber, as a result of

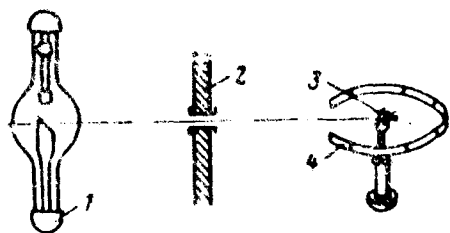


Fig. 3.7. Diagram of X-ray diffraction. 1 - X-ray tube, 2 - slit, 3 - investigated sample, 4 - sensitive film.

investigation of phase transformations and processes occurring during heat treatment.

3.4. Thermal Analysis

Thermal analysis is important method of investigation of metals and alloys. Thermal analysis consists in determination of temperatures of transformations (critical points) during

cooling and heating of metals and alloys by means of plotting "time - temperature"

curves. Any phase transition occurring in metal or alloy is accompanied by evolution (during cooling) or absorption (during heating) of heat.

Therefore if in alloy no phase transitions occur, curve of cooling (heating) will be smooth. In the presence of phase transformations on curve will be horizontal lines or breaks.

These horizontal sections or breaks permit one to determine temperature of transformations.

During conduction of thermal analysis are applied special instruments, allowing exact measurement of high temperatures.

For determination of temperatures the most widely used are thermoelectric pyrometers. Thermoelectric pyrometer (Fig. 3.8) consists of thermocouple and

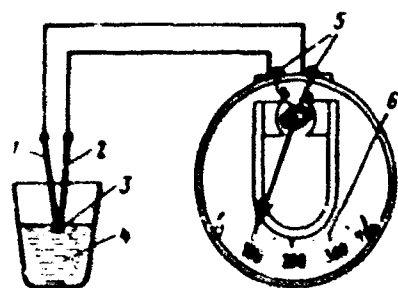


Fig. 3.8. Thermoelectric pyrometer. 1, 2 - wires of thermocouple, 3 - junction, 4, 5 - terminals of galvanometer, 6 - scale of galvanometer.

galvanometer. Thermocouple constitutes two wires 1 and 2 of different metals or alloys, welded at one end 3. Free ends of wires are connected to terminals 4 of galvanometer. When junction of wires is heated in closed circuit appears thermo-emf and pointer of galvanometer is deflected. The higher the temperature of junction of wires the bigger the deflection of pointer.

The most widely used are thermocouples: chromel-alumel (measuring temperature to 1300°C) and platinum-platinum-rhodium (measuring temperature to 1800°C).

For determination of high temperatures also are used optical and radiation pyrometers. They permit to measure temperature at distance without introduction of instruments into the investigated medium. Principle of action of optical and

radiation pyrometers is based on measurement of value of radiant energy of heated bodies.

§ 4. Other Methods of Investigations

During investigation of metals and alloys are applied also methods of electrical resistance and magnetic analysis. These methods are based on the fact that during change of composition or structure of alloy its electrical resistance and magnetic properties are changed. These methods are based on the fact that with change of composition or structure of alloy its electrical resistance and magnetic properties are changed. Knowing law of change of these characteristics with composition and structure of alloy, from magnitude of electrical resistance and magnetic properties one can judge chemical composition and structure of some or another alloy.

CHAPTER IV

PHYSICAL METHODS OF INSPECTION OF METALS AND ALLOYS (DEFECTIONOSCOPY)

Quality of parts of contemporary aviation technology which work under conditions of high speeds of high temperatures, and considerable loads should be exclusively high. They are obliged to correspond to requirements of high strength, reliability, and longevity in exploitation.

Increase of strength, reliability, and longevity of aviation parts is attained by means of application of new high-strength alloys, special surface hardening of parts, improvement of technology of mechanical and heat treatment.

However, in practice there occur cases when in finally prepared part are internal flaws of metallurgical origin or defects appearing sometimes in process of welding, forging, casting, heat treatment or machining. Use of such parts is extremely undesirable, since defects may cause their premature destruction and breakdown. Therefore during manufacture, exploitation, and repair of aviation materiel one of the most important problems is timely detection of flaws in parts and assemblies.

Totality of methods and inspection procedures for parts without their destruction is called defectoscopy.

At present the following physical methods of defectoscopy of parts are widely applied: magnetic, luminescent radioscopy, X-ray and gamma-ray, ultrasonic, and others.

§ 1. Magnetic Defectoscopy

Magnetic method of inspection is used for check of quality of steel ferromagnetic parts and assemblies without their destruction and damage.

medium this, change of magnetic properties of metal in process of its treatment is used also for quality inspection of heat-treated articles.

Magnetic method of defectoscopy is based on detection of magnetic fields of scattering appearing above defects in magnetized component.

During magnetization, in steel part appears flow of magnetic lines of force. If in path of force lines a defect is encountered, for instance, a crack or cavity, in this place strong lines will deviate from their normal direction and, striving to circumvent defect, will exceed the limits of part, forming on its surface local magnetic field of scattering (Fig. 4.1). This field, and consequently the



Fig. 4.1. Field of scattering of magnetic flux at point of defect.

defect also, can be easily detected. Article is magnetized with help of electromagnet and then covered with water containing fine magnetic powder or is covered with dry magnetic powder. Powder is drawn to region of greatest heterogeneity of magnetic field, located at cracks to a depth of up to 2 mm from

surface. On surface of metal appear characteristic accumulations of powder, easily detected during inspection. In such a way it is possible to detect cracks of any origin (hardening, grinding, welding, hairline cracks, flocs, etc.).

In Fig. 4.2 are represented flaws of parts revealed by magnetic defectoscopy

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Fig. 4.2. Flaws of parts revealed by magnetic defectoscopy. a) grinding cracks on bolt of aircraft chassis, b) fatigue crack on welded seam of aircraft chassis assembly.

§ 2. Luminescent Defectoscopy

Luminescent method of inspection is used for detection of surface cracks of parts made from nonmagnetic metals and other materials.

Luminescent method of inspection is based on use of phenomenon of fluorescence,

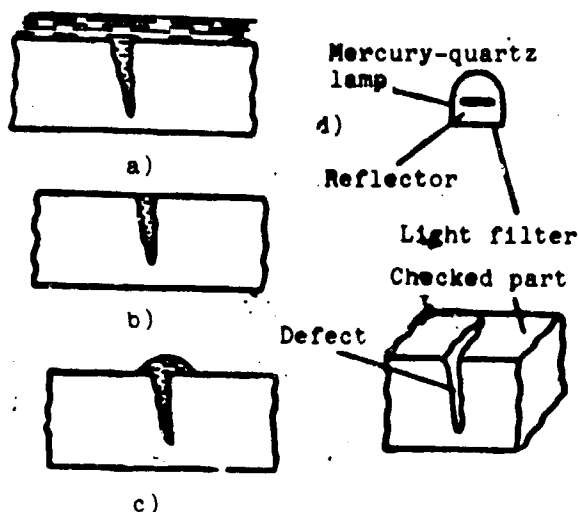


Fig. 4.3. Diagram of luminescent method of defectoscopy. a) penetration of liquid into crack, b) removal of liquid from surface of part and its drying, c) extraction of liquid from crack with help of magnesium oxide, d) illumination by ultraviolet rays and detection of defects.

i.e., glow of certain substances under influence on them of invisible ultraviolet beams. Such substances include mineral oils, certain salts, and their solutions: lumogen, anthracence, defektol', rhodamine, etc. These substances are able to absorb energy of ultraviolet rays and immediately radiate it in the form of glow. After cessation of influence of ultraviolet rays glow of substances vanishes. Each of fluorescent substances possesses its own characteristic glow color. Thus, for example, mineral oil MK under ultraviolet illumination gives bluish-white glow, lumogen gives yellow glow, defektol' gives yellowish-green, etc.

In Fig. 4.3 is shown diagram of luminiscent method of defectoscopy. Investigated part is covered with "active" liquid, which penetrates all pores, cracks, and other surface deepenings. Surplus of liquid is then removed from surface of part and on the latter is deposited any powder able to easily be absorbed in this liquid (for instance, burnt magnesia). Liquid getting in cracks is extruded by particles of powder, which permits on to location and form of cracks through subsequent irradiation of part by light of mercury-quartz lamp. Beams of visible spectrum radiated by lamp are trapped by filter of dark uviol glass. At place of crack appears bright luminescent line corresponding to it in configuration and extent.

By luminescent method are well revealed shrinkage cracks in castings, quenching and grinding cracks, cracks in welded seams, and so forth.

This method does not guarantee detection of cracks filled with products of corrosion, nonmetallic inclusions, or those bearing character of wide scratches. Therefore parts made from ferromagnetic metals subject to luminescent inspection only in those cases when magnetic inspection for some or other causes cannot be applied.

In Fig. 4.4 is presented flaw of part (crack of blade of turbine stator of gas

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Fig. 4.4. Flaw of part revealed by luminescent defectoscopy (crack of blade of turbine stator).

turbine) detected by luminescent defectoscopy.

§ 3. Radioscopy by X- and Gamma-Rays

Radioscopy with help of X-rays (X-ray defectoscopy) or gamma-rays (gamma defectoscopy) is used for inspection of parts for the purpose of manifestation of internal flaws (cavities, porosity, etc.).

For this are used powerful X-ray installations with voltage of 200-300 kV or radioactive isotopes. Installations require attachments for protection of maintenance personnel from harmful influence of radiation.

X-ray flaw detector (radioscopy, photography) is based on property of X-rays to penetrate through bodies not transparent to visible rays, for instance, through metals and alloys. Here, with passage through article occurs dispersion and absorption of X-rays in material of article because there intensity decreases. Decrease of intensity depends on wavelength of X-ray, and also on material and thickness of article. The less the wavelength the greater the penetrating ability of rays. In connection with this, rays with great penetrating ability (shortwave) are called rigid and those with low penetrating ability (longwave) are soft.

X-rays directed towards part in which heterogeneities are structural (cavities, tighter inclusions, and so forth), after passage through part will possess unequal intensity. More intense will be beams encountering different voids on their way (cavities, blowholes, cracks, porous sections, etc.). In corresponding places on photographic film appear dark spots having contours of these defects (see diagram in Fig. 4.5).

Conversely, intensity of beams passed through inclusions denser than material of part (for instance, liquational inclusions of copper in aluminum alloys) will be considerably weakened, and such beams will cause brightening on negative film. On positive print relationship of light and dark areas will be correspondingly reversed.

This is basis for X-ray photography, allowing one to inspect quality of parts.

Conditions of photography depend on many factors: the most important is exposure time (holding), determined by quality of material, thickness of article,

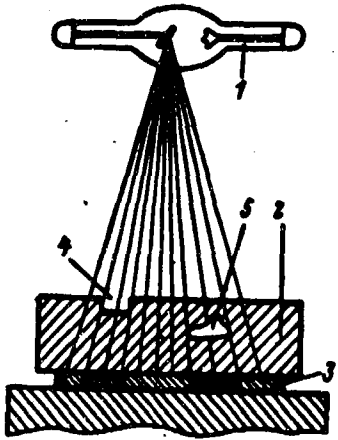


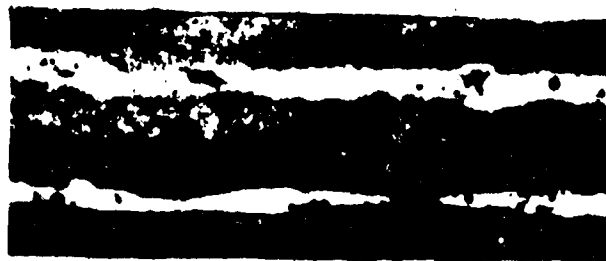
Fig. 4.5. Diagram of radioscopy by X-rays. 1 - X-ray tube, 2 - transilluminated metal, 3 - cassette with film, 4 - cut in metal, 5 - cavity.

voltage in tube, and force of working current.

Radioscopy of parts and subsequent photography is called by photographic method, and radioscopy with examination of defects on screen is called visual method.

Photographic method is considerably more sensitive than visual and permits transilluminating large thicknesses of steel (to 40-50 mm). Therefore it has found widest application. Visual radioscopy is less sensitive, but it is faster and cheaper; it is applied during defectoscopy of parts made from light alloys with thickness of not more than 40 mm and steel of not more than 8 mm in thickness.

X-ray photography is widely applied mainly for quality inspection of parts made from aluminum and magnesium alloys, for the purpose of detection in them casting defects (cavities, pores, friability and gas bubbles) and flaws of pressure treatment (internal rents, cracks, and so forth), and also for investigation of quality of welded seams in steel articles (nonfusion, overburning, cracks, etc.). As example, in Fig. 4.6 are given X-ray photographs of welded seams.



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Fig. 4.6. X-ray photographs of welded seams.

Gamma-defectoscopy. At present ever greater use is being found for methods of quality inspection of parts founded on use of gamma rays. Application of gamma rays has considerably expanded the assortment of transilluminatable parts with respect to their composition and thickness.

Gamma rays are shortwave electromagnetic oscillations, and in nature they do not differ from other forms of radiation - radio waves, visible light, ultraviolet radiation, and X-rays. The only distinction between them and X-rays is in

conditions of formation. Gamma rays appear as a result of radioactive disintegration of nuclei of natural and artificial radioactive substances.

The greater the energy of gamma rays the shorter the wavelength and the higher the penetrating ability. In penetrating ability the majority of radioactive substances gives very hard radiation.

As sources gamma rays earlier served as natural radioactive elements: radium, mesothorium, radiothorium, and also their mixtures. These elements are very deficient and cheap; therefore their application for defectoscopy was limited. Wide use in industry for radioscopy of parts has been made of gamma rays only in recent years, when it has become possible to obtain in sufficient quantity cheap artificial radioactive isotopes of different chemical elements giving gamma radiation of different rigidity: cobalt - 60, cesium - 137, iridium - 192, and others. Mentioned preparations are placed in metallic ampules, which absorb beta radiation (flux of negatively charged particles - electrons). Ampules are stored and transported in lead containers (protective housings), thickness of walls of which is determined by rules of protection of personnel and safety personnel during work with fissionable materials, depending upon activity and energy of radiation of radioactive preparation.

Photographic method of radioscopy of parts by gamma rays coincides with method of radioscopy by X-rays. To obtain photograph, radioactive preparation (Fig. 4.7) is on one side of transilluminated part and on the other is placed cassette with photographic film. After radioscopy and processing of film, gamma photograph is obtained.

Method of gamma defectoscopy possesses series of essential advantages over X-ray method, in view of portability of source of radiation and simplicity of applied equipment. Small dimensions of equipment facilitate its transportation and installation on inspected objects, make it possible to inspect directly on objects. High penetrating ability of gamma rays permits one to inspect more massive parts (for instance, steel parts with thickness of up to 250 mm). However, in sensitivity method of gamma inspection is somewhat inferior to X-ray method. Sensitivity of method of gamma defectoscopy depends on energy of gamma rays (i.e., on source of radiation used), density, and thickness of transilluminated material, and also on character of defect.

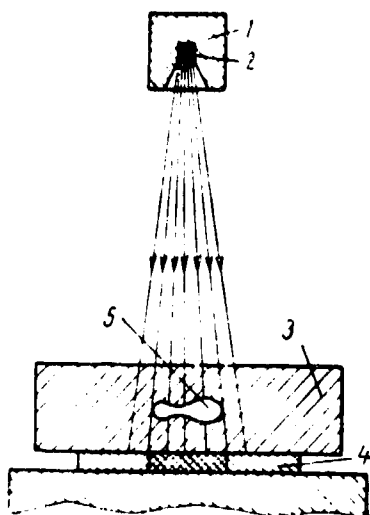


Fig. 4.7. Diagram of radioscopic inspection by gamma rays. 1 - protective housing, 2 - radioactive preparation, 3 - transilluminated part, 4 - cassette with film, 5 - cavity.

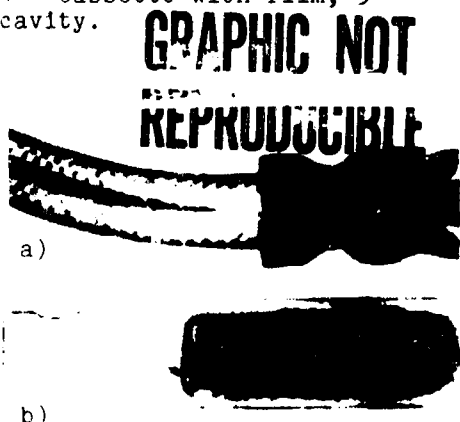


Fig. 4.8. Gamma photographs of parts with internal defects. a) fuel hose, b) rod of exhaust valve.

Gamma radioscopic inspection, like X-radioscopic inspection, makes it possible to inspect parts for the purpose of detection of internal flaws and malfunctions. In Fig. 4.8 are given gamma photographs of aviation parts with internal defects.

§ 4. Ultrasonic Defectoscopy

By method of ultrasonic defectoscopy are inspected parts of any materials in which ultrasonics can spread.

Ultrasonics are oscillations having frequency of more than 20 thousand cps (20 kilocycles), i.e., lying beyond the borders of upper threshold of human audibility. In practice, for purposes of ultrasonic defectoscopy) are applied ultrasonics of frequency from 100 kilocycles to 10 Mc (10 million cps), obtained by artificial means.

With such frequencies wavelength of ultrasonics passing through metal is from 0.5 to 30 mm and is commensurable with dimensions of defects.

As source of ultrasonic oscillations serve as piezoelectric radiators, basic part of which is

piezoquartz plate, cut in a determined way from quartz crystal. This plate possesses property of piezoelectric effect, consisting in that during compression or extension of plate in defined direction on its surface appear charges whose sign is determined by direction of deformation and magnitude is determined by applied force (Fig. 4.9). Reverse piezoelectric effect appears if such plate is introduced into electrical field, which results in change of its dimensions in accordance with intensity and direction of field. If field is variable, the plate will accomplish forced oscillations with frequency of field. Thus, it is possible to use this plate as radiator

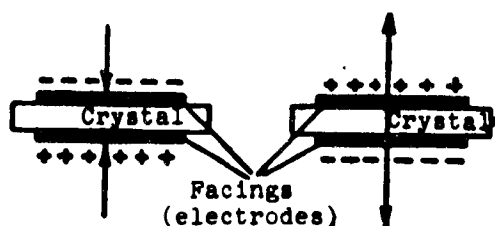


Fig. 4.9. Diagram of piezoelectric effect.

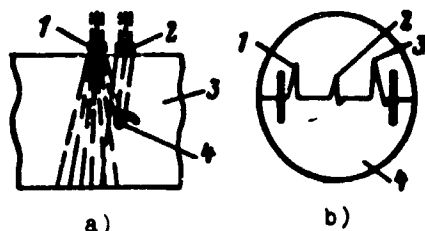


Fig. 4.10. Diagram of ultrasonic defectoscopy. a) part with defect. 1 - radiator, 2 - receiver, 3 - part, 4 - defect. b) screen with signals. 1 - initial signal, 2 - echo-signal from defect, 3 - bottom signal, 4 - electron-beam tube.

of ultrasonic oscillations [US] (V3K), sending them to alternating voltage.

Recently, instead of quartz plate, there have been applied less scarce plates of barium titanate, which also possesses piezoelectric effect.

Contemporary ultrasonic defectoscopy is based on reflection of ultrasonic waves from defects in material and catching of reflected waves by special receiving-amplifying devices.

Principle of operation of ultrasonic flaw detector consists of the following (Fig. 4.10). With the aid of vacuum-tube oscillator are created electrical waves, which then go to piezoelements. The latter converts electrical oscillations to ultrasonic, signal which on screen of oscillograph is seen in the form of peak (initial signal). In the absence of defects this impulse passes inside

part to its opposite face ("bottom"), and, being reflected, returns to receiver.

Reflected electrical oscillations go through amplifier to screen of oscillograph. On screen appears second peak (bottom signal). When defect is encountered along the path of beam, on screen there appears a third peak, corresponding to reverse signal from defect. It is located between peaks corresponding to initial and bottom signals. From distance to this peak one can determine depth of defect.

An important advantage of this method is possibility of detection of defects at large depths (to 3 m). Therefore it is especially valuable for inspection of big castings, forgings, stampings, and such articles.

CHAPTER V

STRUCTURE AND CRYSTALLIZATION OF ALLOYS

§ 1. Bases of Structure of Alloys

Concept of alloys. Pure metals do not possess necessary complex of properties imposed on materials for parts of contemporary machines. Therefore of predominant application in technology are not pure metals but their alloys. Alloys are distinguished by higher strength properties than metals. However, they possess lower plasticity, electrical conductivity, and differ by a series of other physical properties.

Contemporary stage of development of technology is characteristic for the fact that along with increase of quantity of alloys and complication of their composition, metals of high purity are obtaining value. They are applied widely in atomic, electronic, and other branches of new technology.

An alloy is a complicated metallic body, consisting of two or more elements, obtained by their fusion, sintering, or other methods. Metallic alloys consist of metals but may also contain nonmetallic elements. However, in this case preservation by alloy of properties inherent to metals is obligatory. In every alloy we distinguish components and phases. Components are substances forming alloy. Phase is uniform part of alloy, separated from other parts of alloy by interface. In liquid state alloy most frequently contains one phase. During hardening there always are two phases - liquid and solid.

After hardening, one or several phases is formed. In liquid state majority of metallic alloys applied in technology constitute uniform liquids - solutions of components.

Structural components of alloys. Components of alloys possessing different properties enter into different interactions, forming metallic bodies of more complicated structure than pure metals. During hardening there occur processes leading to formation in alloy of following structural components: mechanical mixtures, solid solutions, chemical compounds. Properties of alloy depend on properties of structural components.

Mechanical mixture is formed if components of alloy do not interact with each other chemically but are in alloy in the form of independent interconnected grains. Alloys of such kind are nonuniform. Every component of alloy is crystallized in separate grains having crystal lattice inherent to given component (Fig. 5.1).

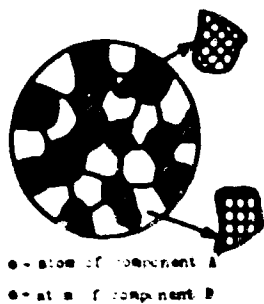


Fig. 5.1. Structure of mechanical mixture.

Mechanical mixture is formed by alloys of lead and antimony or tin and zinc. Besides this, mechanical mixture can be formed not only by grains of pure elements but also by grains of solid solutions and chemical compounds.

Solid solution is formed when components of alloy possess solubility in solid state. Solid solutions are compounds formed by means of penetration into crystal lattice of metal-solvent of atoms of dissolved metal. Solvent is an element whose crystal lattice is preserved during formation of solid solution.

Thus, for alloys possessing structure of solid solutions crystal structure of basic metal is kept and grains are uniform (Fig. 5.2).

In solid solutions can occur diffusion processes. Diffusion rate increases with increase of temperature and depends on difference of concentrations.

Properties of solid solutions are not similar with properties of component parts but do not differ sharply from them and depend on quantity of soluble metal. For

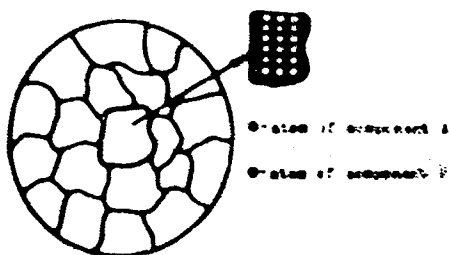


Fig. 5.2. Structure of solid solution.

instance, alloys of copper and zinc can have different properties, depending upon how much zinc is dissolved in copper.

Solid solutions can be of unlimited and limited solubility. In last case in crystal lattice of metal-solvent can enter only defined limited quantity of atoms of soluble metal. During formation of solid solutions of limited solubility, the

latter strongly depends on temperature. Usually with increase of temperature solubility is increased.

Depending upon distribution of atoms of dissolved metal in crystal lattice of metal-solvent we distinguish two forms of solid solutions: substitutional solid solutions and interstitial solid solutions.

In substitutional solid solutions atoms of dissolved component replace atoms of solvent (Fig. 5.3b). During formation of interstitial solid solutions, atoms of dissolved element are placed between atoms of solvent (Fig. 5.3c).

It has been established that substitutional solid solutions form metals whose atoms differ in dimensions by not more than 15% (for instance, copper and nickel, iron and chromium). Interstitial solid solutions are formed most frequently when metal dissolves in itself nonmetallic elements whose atoms are considerably smaller than atoms of metal (for instance, iron and carbon, iron and nitrogen).

Chemical compounds are obtained during interaction of components of alloy. They have constant composition, unique crystal lattice, and special physical, chemical, and mechanical properties. To chemical compounds in alloys are peculiar raised hardness and brittleness. Chemical compounds can be formed during interaction both of metals with metals and also of metals with metalloids. For instance, in iron-carbide alloys there forms a chemical compound of iron with carbon Fe_3C (so-called cementite); in alloys of aluminum with copper CuAl_2 forms, etc.

Chemical compounds in structure of alloy are in isolated state. When alloy is heated, crystals of chemical compounds can be dissolved in solid solution of

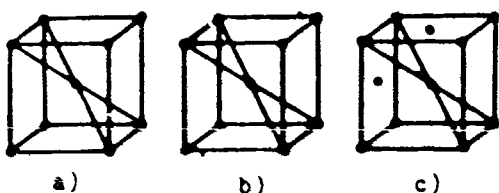


Fig. 5.3. Crystal lattices. a) pure metal, b) substitutional solid solution, c) interstitial solid solution.

alloy, and with lowering of temperature these form anew.

With respect to quantity of components entering in alloy, we distinguish binary, ternary, and more complicated alloys.

Alloys applied in technology have complicated chemical composition. High-strength

steels, for instance, have in their composition up to ten different chemical elements. The more complex the composition and structure of an alloy the more varied its properties usually are.

§ 2. Constitutional Diagrams of Alloys

Constitutional diagrams of metallic systems show change of state of alloys depending upon concentration of components and temperature. Constitutional diagrams characterize results of interaction of components in system during change of composition or temperature, which makes it possible to select correctly conditions of hot and heat treatment of alloys.

Constitutional diagrams are constructed in the following way.

At first, with help of thermal analysis, curves of cooling of alloys of different compositions are obtained. On these curves are found points of inflection and horizontal sites, characterizing critical temperatures of corresponding alloys. Then, on "temperature - concentration" coordinates is constructed constitutional diagram, onto which are transferred critical points of transformations of all alloys. Constitutional diagram is obtained by connection of these points (Fig. 5.4).

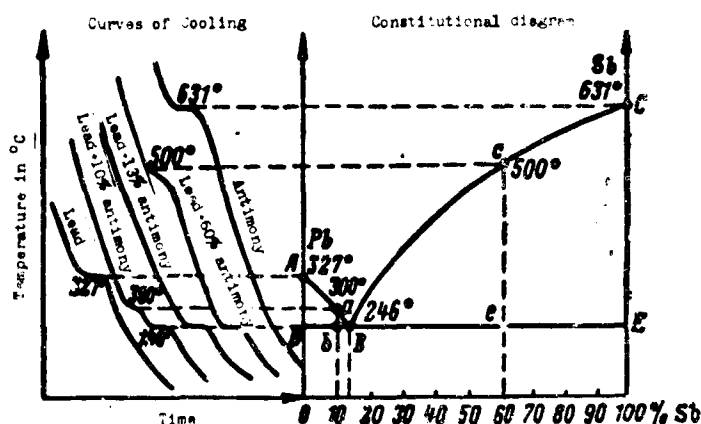


Fig. 5.4. Construction of constitutional diagram of alloys of lead-antimony from curves of cooling system.

Obligatory condition for construction of similar diagrams is slow cooling of alloys, ensuring full course of all transformations and obtaining of stable state.

The more components in alloy the more complicated the form of constitutional diagram. Thus, for two-component system diagram is constructed in rectangular system of coordinates, where on axis of ordinates is plotted temperature and on axis of abscissas is plotted concentration of components. Diagram of three-component system is reproduced in space: Two axes, located on plane intended for appraisal of concentrations and one spatial, intended for appraisal of temperature.

Constitutional diagrams of alloys are similar if their components form

identical structures upon hardening.

There are several forms of constitutional diagrams of alloys of two components.

§ 3. Constitution Diagram of Type I

Constitution diagram of type I characterizes alloys whose components in liquid state are completely mutually dissolved and in solid state form mechanical mixture of crystals of both components.

In accordance with given constitutional diagram harden alloys: lead - antimony, tin - zinc, lead - silver, and others. In Fig. 5.5 is represented constitutional

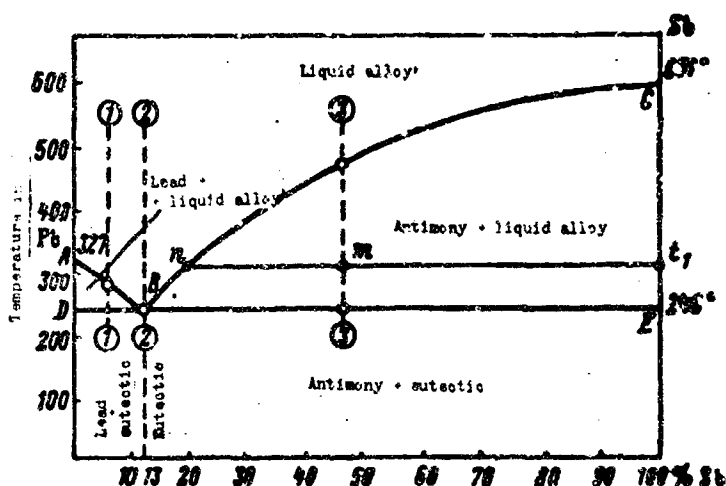


Fig. 5.5. Constitutional diagram of alloys of lead - antimony system.

diagram of alloys of lead - antimony system. On this diagram points on curve ABC show for every alloy of lead and antimony temperature at which alloy begins to harden, and points on line DE show temperature at which hardening is finished.

Upper line ABC is called liquidus curve (from Latin "liquidus," meaning "liquid").

Lower line DE is called solidus ("solidus" means "hard"). Above

liquidus alloys are in liquid state and below solidus they are in solid state.

At point B for content of 13% Sb and 87% Pb at a temperature of 246°C crystallization of lead and antimony occurs simultaneously; there forms a special mechanical mixture of crystals of lead and antimony. This mixture is called eutectic and alloy of corresponding composition is called eutectic alloy (alloy 2-2 in Fig. 5.5). Eutectic alloy has the lowest melting point of all alloys of given system.

Microstructure of lead - antimony eutectic alloy is shown in Fig. 5.6c.

Alloys containing less than 13% antimony (left of B) are called hypoeutectic (for instance, alloy 1-1 in Fig. 5.5). For them on line AB from liquid crystals of lead start to separate until liquid part of alloy is impoverished of lead to 87%. On line DE it is crystallized with formation of eutectic. After crystallization of

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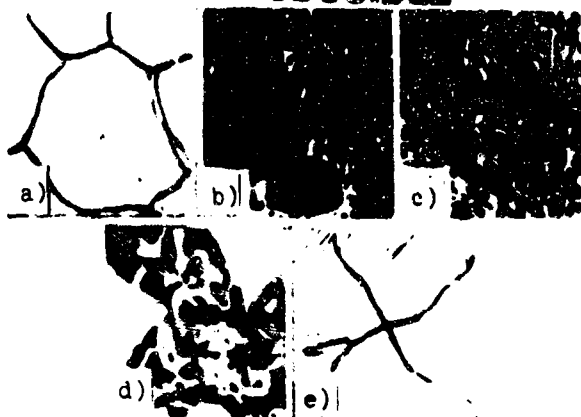


Fig. 5.6. Microstructures of lead - antimony alloys, $\times 200$. a) pure lead, b) hypoeutectic alloy, c) eutectic alloy, d) hypereutectic alloy, e) pure antimony.

hypoeutectic alloys, they have structure consisting of eutectic and excess lead. In Fig. 5.6b is represented structure of hypoeutectic alloy (dark grains of lead and eutectic between them).

Alloys containing more than 13% antimony (right of point B) are called hypereutectic (for instance, alloy 3-3 in Fig. 5.5). Crystallization of hypereutectic alloys begins on line BC with separation of excess antimony, and on line DE occurs hardening of eutectic.

After hardening of hypereutectic alloys, they have structure consisting of eutectic and excess antimony. In Fig. 5.6d is represented structure of hypereutectic alloy (light grains of antimony and eutectic between them).

Structure of pure lead is represented in Fig. 5.6a and that of pure antimony in Fig. 5.6e.

For determination of quantity of liquid and solid phase of alloy at given temperature we use "rule of lever." According to this rule, ratio of quantity of liquid phase to quantity of solid is proportional to the ratio of segments opposite them. If we consider this relationship on diagram (see Fig. 5.5, alloy 3-3 at point m) at temperature t_1 , it will take form

$$\frac{\text{quantity of liquid solution}}{\text{quantity of antimony crystals}} = \frac{mt_1}{nm}$$

If in alloys forming mechanical mixture during crystallization, components of which differ in specific gravity, we decrease cooling rate, crystals of separated excess component will not be evenly distributed in liquid alloy. Heavier crystals will be precipitated on bottom of casting mould or form. In this case up to moment of full crystallization, when liquid solution forms eutectic, the latter will be chiefly above and crystals of heavier excess component chiefly below. As a result, chemical composition of ingot or casting will be nonuniform.

Thus, in hypoeutectic alloys crystals of lead can settle on bottom of form, and

in hypereutectic alloys lighter antimony can surface. Such chemical heterogeneity is called liquation.

From constitutional diagram one can determine inclination of alloys of given system to liquation. The less the distance between liquidus and solidus on constitutional diagram the less the inclination of alloys of given system to liquation.

§ 4. Constitutional Diagram of Type II

Constitutional diagram of type II characterizes alloys whose component possess full mutual solubility both in liquid and in solid state, i.e., are able to form solid solutions of unlimited solubility.

In accordance with this constitutional diagram are crystallized the following alloys: bismuth - antimony, copper - nickel, iron - nickel, iron - chromium, iron - vanadium, and others.

In Fig. 5.7 is depicted constitutional diagram of bismuth - antimony alloys.

Through critical points of beginning and end of hardening of alloys of different concentration of bismuth and antimony are drawn curves ACB and ADB. The

first of them is liquidus and second is solidus.

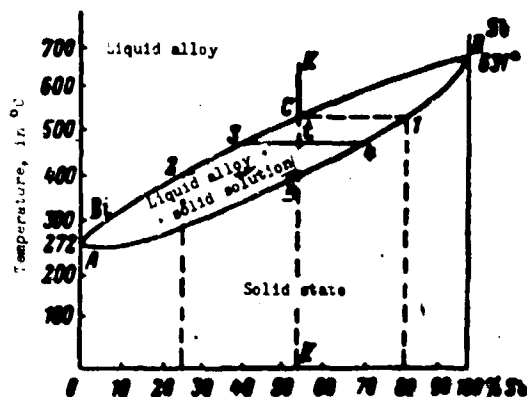


Fig. 5.7. Constitutional diagram of alloys of bismuth - antimony system.

On constitutional diagram are three regions: region of liquid alloy (above liquidus ACB), region of uniform solid solution (below solidus ADB), and region where alloy consists of liquid and crystals of solid bismuth - antimony solution (between liquidus ACB and solidus ADB).

During hardening of alloys in accordance with constitutional diagram of type II, composition of crystals of solid solution and composition of liquid phase continuously change. During hardening of any alloy, in process of crystallization grains of solid solution enriched by more refractory component are separated.

Let us consider process of hardening of alloy containing 45% antimony. Point C on liquidus corresponds to temperature of beginning of crystallization of given

alloy. Above point C alloy is in liquid state. At point C crystallization of alloy starts. Grains are formed of solid bismuth - antimony solution. These crystals are of variable composition, changing along line 1-D. Concentration of liquid alloy changes along line C-2. At point D crystallization of alloy is completed.

Composition of phases in process of hardening is determined by intersection points of horizontal with liquidus and solidus lines. At temperature t composition of liquid phase is determined by projection of point 3, lying on liquidus, and composition of solid phase is determined by projection of point 4, lying on solidus.

Relationship between quantity of liquid alloy and quantity of crystals of solid solution, according to rule of the lever, is determined by ratio t_4/t_3 .

By determining composition of phases at different temperatures in process of hardening one can see that first crystals of solid solution are enriched by refractory component (antimony) and that with lowering of temperature both liquid and solid solutions are enriched by fusible component (bismuth).

Toward the end of hardening crystals of solid solution have to be uniform, i.e., have identical chemical composition, corresponding to initial composition (Fig. 5.8b). Levelling of composition occurs by means of diffusion. During slow cooling the process of diffusion succeeds in completion. Under conditions of fast cooling diffusion does not succeed in levelling composition of separate crystals and central part of dendrites will be richer in refractory component and periphery richer in fusible component (Fig. 5.8c). Such chemical heterogeneity, observed in different places of dendrites, is called dendritic liquation. Structure

of pure bismuth is represented in Fig. 5.8d.

§ 5. Constitutional Diagram Type III

Constitutional diagram of type III characterizes alloys whose components possess unlimited solubility in liquid state and limited solubility in solid state, i.e.,

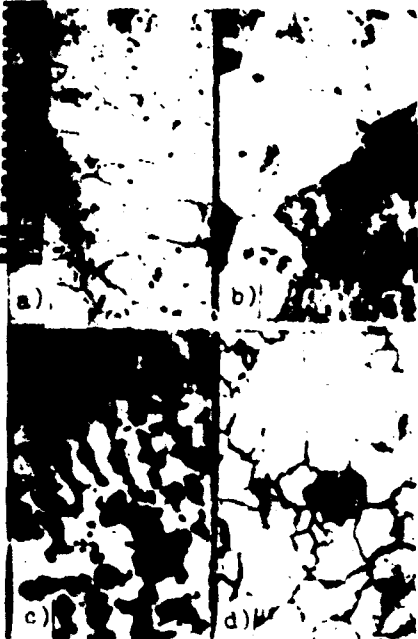


Fig. 5.8. Microstructure of bismuth - antimony alloys. $\times 300$. a) pure bismuth, b) uniform bismuth - antimony solid solution, c) nonuniform bismuth - antimony solid solution, d - pure antimony.

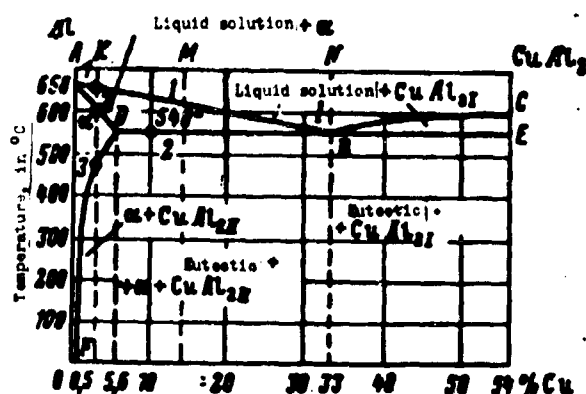


Fig. 5.9. Constitutional diagram of aluminum - copper alloys.

form solid solutions of limited solubility, decreasing with lowering of temperature.

Such diagram characterizes hardening of alloys of systems aluminum - copper, aluminum - silicon, copper - silver, and others.

In Fig. 5.9 is given constitutional diagram of Al - CuAl₂, of presenting part of Al - Cu diagram.

Line ABC is liquidus curve; above this line all alloys are in liquid state.

Line ADBE is solidus.

In aluminum - copper solid state form solid solutions of limited solubility. Maximum concentration of solution of copper in aluminum is 5.6% at a temperature of 548° (point D). With higher concentration along line DBE is formed eutectic consisting of solid solution and chemical compound.

Curve DF is line of maximum solubility of copper in aluminum. It shows that with cooling of alloys below line of eutectic (DBE), solubility of copper in aluminum drops and at room temperature is 0.5% (point F).

All alloys of system Al - CuAl₂, according to copper content, may be subdivided into the following groups: from 0 to 5.6% alloys without eutectic, from 5.6 to 33% hypoeutectic alloys, 33% contains eutectic alloy, and from 33 to 54% hypereutectic alloys.

Let us trace crystallization of alloy without eutectic K, hypoeutectic alloy M, and eutectic alloy N.

Alloy K above point 1 is in liquid state. At temperature 1 crystallization starts and crystals of solid solution α are separated. At temperature 2 crystallization is finished and formed crystals of solid solution α undergo no changes to point 3. Owing to the fact that solubility of copper in aluminum changes along line DF, below point 3 solid solution α turns out to be oversaturated by copper, i.e., contains more copper than can be in solid solution at these temperatures. This excess part will be separated from solid solution in the form of secondary crystals of chemical compound CuAl₂.

By secondary crystals are understood those separated from solid solution (they are designated by index II) in distinction from primary crystals separated from liquid (they are designated by index I). Singling out of crystals of $\text{CuAl}_{2\text{II}}$ will continue to full cooling, when solid solution takes composition corresponding to point F. Final structure of alloy will consist of crystals of solid solution α and chemical compound $\text{CuAl}_{2\text{II}}$ (Fig. 5.10b).

Alloy M at temperature 1 starts to crystallize, grains of solid solution α are separated. At eutectic temperature 2 liquid part of alloy takes composition corresponding to point B. Hardening will occur with formation of eutectic, consisting of mixture of crystals of solid solution α of composition of point D and chemical compound CuAl_2 . During further cooling of alloy from solid solution α will be separated excess crystals of $\text{CuAl}_{2\text{II}}$, as during cooling of alloy K below temperature 3. Final structure of alloy will

Fig. 5.10. Microstructures of aluminum - copper alloys. $\times 200$. a) pure aluminum, b) alloy without eutectic, c) hypoeutectic alloy, d) eutectic alloy.

consist of eutectic, crystals of solid solution α , and excess crystals of $\text{CuAl}_{2\text{II}}$ (see Fig. 5.10c). Alloy N above point 1 has liquid state. At temperature 1 will occur crystallization of alloy with formation of eutectic (see Fig. 5.10d). Structure of pure aluminum is presented in Fig. 5.10a.

§ 6. Constitutional Diagram of Type IV

Constitutional diagram of alloys type IV characterizes alloys whose components are soluble without limit in liquid state, insoluble in solid state, and form stable chemical compound.

Constitutional diagram of type IV is shown in Fig. 5.11.

Vertical line CD on diagram corresponds to chemical compound A_mB_n , formed by components A and B. Point C corresponds to melting point of chemical compound A_mB_n and is called singular point.

On diagram are two eutectic points E_1 and E_2 . Eutectic alloy E_1 constitutes mechanical mixture of crystals of A and chemical compound A_mB_n , and eutectic alloy E_2 is mechanical mixture of crystals of B and chemical compound A_mB_n . Crystallization

of alloys per this diagram occurs just as crystallization of alloys of type I, only in this case there forms a mechanical mixture not of components A and B but mechanical mixture of chemical compound A_mB_n and crystals of component A or B. Regions formed

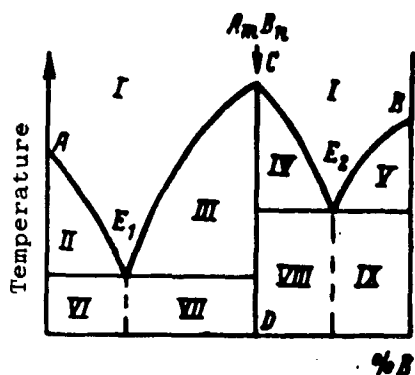


Fig. 5.11. Constitutional diagram in case of formation of chemical compound.

by diagram are characterized by following state and structure: region I – liquid alloy; region II – liquid alloy + crystals of A; region III and IV – liquid alloy + crystals of chemical compound A_mB_n ; region V – liquid alloy + crystals of B; region VI – crystals of A + eutectic of composition of point E_1 (crystals of A + crystals of chemical compound A_mB_n); region VII – crystals of A_mB_n + eutectic (crystals of A + crystals of A_mB_n); region VIII – crystals of A_mB_n + eutectic (crystals of B + crystals of A_mB_n); region IX – crystals of B + eutectic (crystals of B + crystals of A_mB_n).

For chemical compound is characteristic strictly defined relationship between components and the circumstance that it is melted at constant temperature.

§ 7. Composition-Property Diagrams

During the analysis of constitutional diagrams it is important to study properties of alloys depending upon their composition. Method of construction of composition-property diagrams was developed by Academician N. S. Kurnakov, who discovered defined dependence between properties of alloys and constitutional diagram.

For construction of composition-property diagrams on axis of abscissas is plotted composition and on axis of ordinates are plotted values of properties measured at constant temperature (hardness, electrical conductivity, density, and others).

In Fig. 5.12 are given basic types of constitutional diagrams considered by us earlier and corresponding composition-property diagrams. Extreme ordinates on composition-property diagrams correspond to properties of pure components, and intermediate ordinates correspond to properties of alloys depending upon their composition.

During formation of mechanical mixtures properties of alloys are changed according to the law of straight line and values of properties of any of alloys are

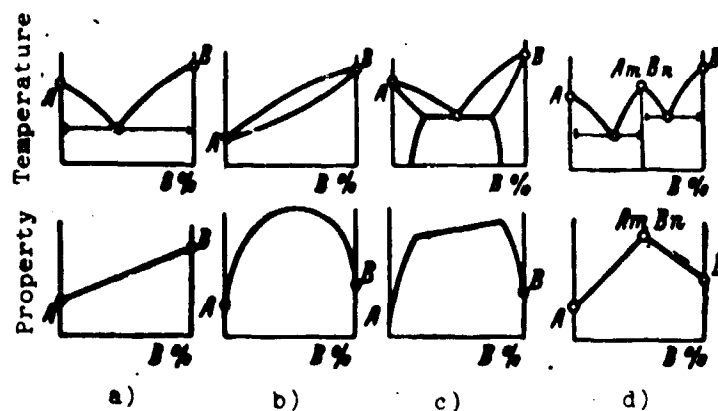


Fig. 5.12. Constitutional diagrams and corresponding composition-property diagrams.

within limits of properties of pure components (see Fig. 5.12a).

During formation of solid solutions properties of alloys are changed per curvilinear dependence, where certain properties can differ considerably from properties of components entering in alloy. Therefore during formation of solid solutions, or during their disintegration, sharp change of shown properties is observed (see Fig. 5.12b).

During formation of limited solid solutions properties are changed in accordance with belonging of some or other part of diagram to type I or II of diagrams.

Thus, properties in interval of concentrations, corresponding to solid solution, are changed per curvilinear dependence, and in region of mechanical mixtures are changed per rectilinear law (see Fig. 5.12c).

During formation of chemical compound properties of alloys are changed in the same way per rectilinear law, but with composition corresponding to chemical compound, on composition-property diagram is observed break of straight line with formation of maximum (see Fig. 5.12d).

Composition property diagrams have important value, since they permit one in practice to correctly approach selection of alloy for defined purposes. For example, alloys with high electrical resistance must be selected from solid solutions, those with high hardness must be found among alloys forming chemical compounds, etc.

CHAPTER VI

PLASTIC DEFORMATION AND RECRYSTALLIZATION OF METALS

§ 1. Plastic Deformation

As was shown, metal in solid state is polycrystalline substance. It consists of large quantity of differently oriented grains of irregular shape (crystallites). Properties of polycrystals in many respects are determined by intrinsic properties of separate grains (single crystals).

Plastic deformation of single crystals. During loading of single crystal, in the beginning appear elastic deformations and elastic distortion of crystal lattice occurs. With increase of stress above defined value irreversible changes of crystal lattice of metal occur. For plastic (residual) deformation it is necessary to subject metal to stress which is greater than elastic limit. Plastic deformation of single crystal occurs by means of slip or twinning.

Slip (shift) consists in parallel displacement of separate parts of single crystal relatively to one another (Fig. 6.1). Slip or shift occurs on defined planes of crystal lattice, the most thickly studded with atoms (so-called glide planes).

Twinning consists in turn of part of crystal to another position symmetric with respect to first part with respect to plane called twinning plane (Fig. 6.2).

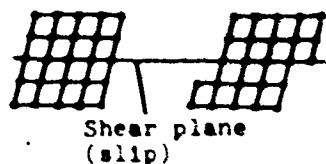


Fig. 6.1. Diagram of slip.

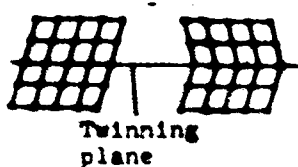


Fig. 6.2. Diagram of twinning.

In region of shift structure of metal sharply changes. In regions adjoining shear plane occurs distortion of crystal lattice. In the actual zone of shift occurs crushing or splitting

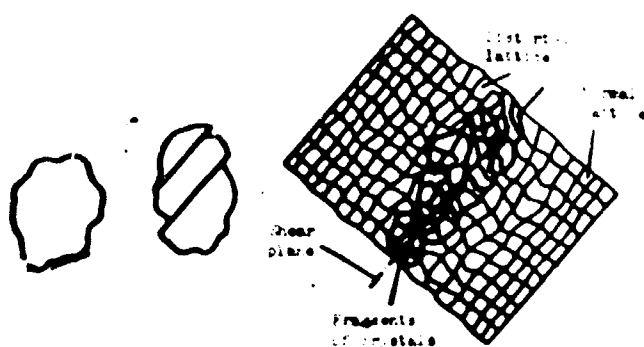


Fig. 6.3. Diagram of change of structure in zone of shear plane.

of grains. All this leads to hardening of metal. In Fig. 6.3 is given diagram of change of structure in zone of shear plane.

Plastic deformation of polycrystals. Plastic deformation of polycrystalline body is more

complicated. In this case, besides slip and twinning of restricted variously oriented neighboring grains, there is observed intergranular shift.

In process of plastic deformation grains are crushed, extruded, and disposed in direction of deformation, forming fibrous structure (Fig. 6.4).

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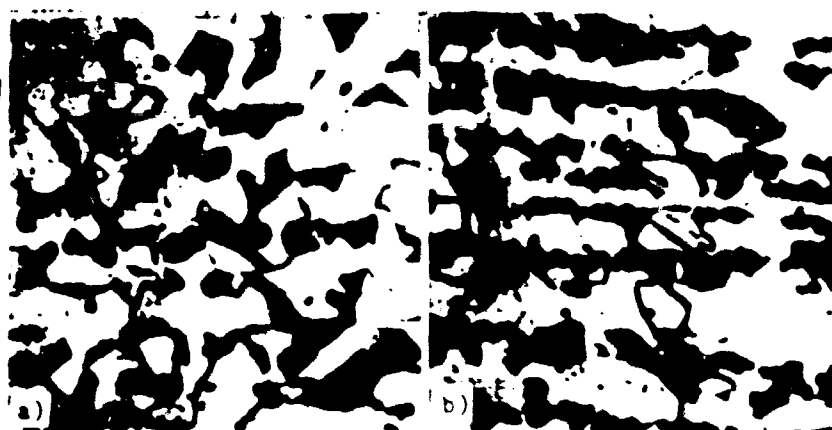


Fig. 6.4. Microstructure of steel. a) before cold deformation, b) after cold deformation.

Fibrous structure of metal is strengthened owing to the fact that impurities present in metal also are split, extruded, and disposed in boundaries of deformed grains.

Plastic deformation of metal in cold state strongly changes its mechanical properties: strength and hardness are increased, ductility and impact toughness drop.

Besides this, there is observed change of physical and chemical properties of metals: corrosion resistance decreases and electrical resistance and residual magnetism are increased.

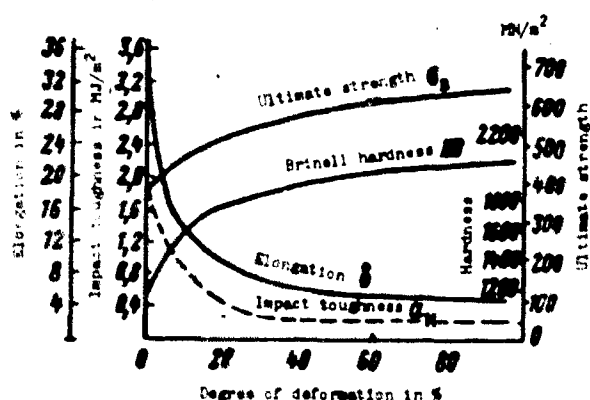


Fig. 6.5. Influence of cold deformation on mechanical properties of low-carbon steels.

Hardening of metal in process of plastic deformation is called cold working. Surface hardening of metal is called work hardening.

In Fig. 6.5 is shown change of mechanical properties of soft steel during cold rolling.

Preferable orientation of grains in work-hardened polycrystalline metal causes anisotropy of its properties. In most cases anisotropy of properties caused by cold treatment is undesirable, but in certain cases it is created intentionally (for instance, in transformer steel for improvement of magnetic properties).

§ 2. Recrystallization

Deformation, causing formation of internal stresses and distortion of crystal lattice, translates metal to unstable state.

Heating of cold-worked metal promotes its transition to stabler form. With heating of cold-deformed metal, in it consecutively occur processes leading to its softening.

During heating to low temperatures occurs recovery of metal. For instance, phenomenon of recovery for iron is observed during heating to temperature of 200-300°C. Recovery considerably lowers internal stresses and removes distortion in crystal lattice without change of microstructure. This leads to slight softening of metal (increase of plasticity and lowering of hardness and strength).

During heating to higher temperatures the process of recrystallization sets in, playing basic role in softening of metal. Recrystallization consists in appearance in deformed metal of centers of crystallization and growth around them of new equiaxial grains with undistorted crystal lattice. As a result of recrystallization there occurs restoration of microstructure, accompanied by full softening of metal (hardness and strength drop and plasticity is increased).

Recrystallization, or so-called recrystallization annealing, serves for removal

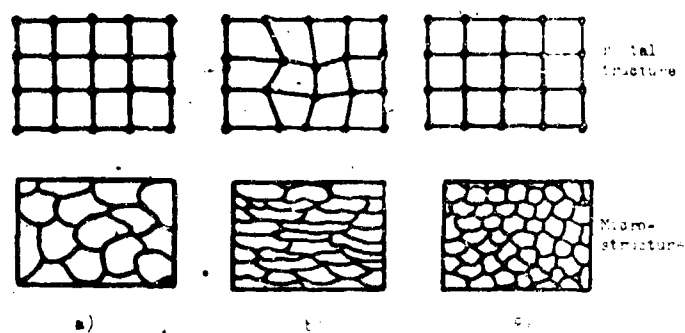


Fig. 6.6. Diagram of change of structure of metal during deformation and recrystallization. a) before deformation, b) plastically deformed metal, c) after recrystallization.

of cold working of metal after cold treatment by pressure.

In Fig. 6.6 are shown schematically changes of structure of metal as a result of plastic deformation and recrystallization.

Distortion of crystal lattice in process of plastic deformation can be detected with help of X-ray diffraction analysis. It is possible to observe deformation of grains and crushing of them after recrystallization under microscope.

Temperature at which new equiaxial grains start to appear is called recrystallization temperature. According to Academician A. A. Bochvar, for every metal there exists a unique recrystallization temperature, constituting 0.4 absolute melting point: $T_{\text{рекр.}} \approx 0.4 T_{\text{пл.}}$

Using this formula, one can determine recrystallization temperature of different metals and alloys. For iron and steel this is approximately 450°C, for copper 280°C, brass 250°C, aluminum 100°C, lead 30°C. Temperature interval of recrystallization annealing for iron and steel is 600-700°C, for copper and brass 400-500°C.

Magnitude of grain obtained during recrystallization depends on temperature of heating of deformed metal and on degree of its deformation. With increase of temperature of recrystallization annealing, dimension of newly formed grains is increased. In still greater degree growth of grain depends on degree of deformation (Fig. 6.7).

Degree of deformation giving maximum dimension of grain during heating is called critical.

For more full characteristic there frequently are constructed three-dimensional diagrams of recrystallization, allowing one to judge growth of grains depending upon deformation and temperature (Fig. 6.8).

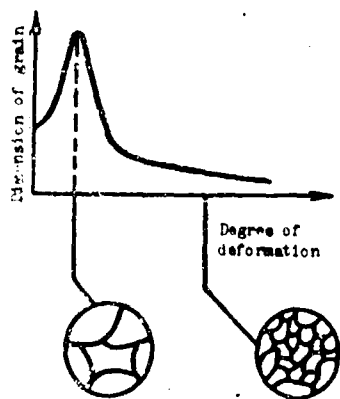


Fig. 6.7. Change of magnitude of grain depending upon degree of plastic deformation.

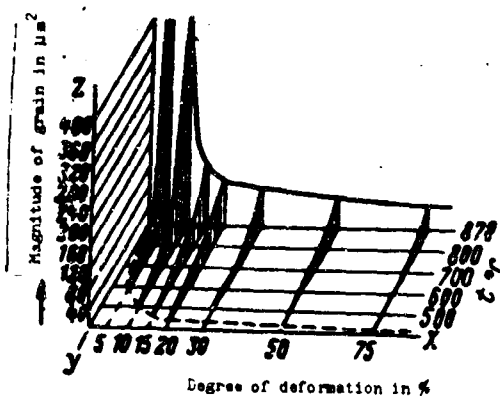


Fig. 6.8. Diagram of recrystallization of soft steel.

Recrystallization has great practical value in technology of treatment of metals and in all cases which are connected with mechanical softening of metal.

CHAPTER VII

IRON - CARBIDE ALLOYS

Alloys of iron with carbon are the most important technical alloys applied in contemporary technology. To iron-carbide alloys pertain steel and cast iron. Iron-carbide alloys containing up to 2% carbon are called steels and those containing more than 2% carbon (practically from 2.5 to 4.5%) are cast irons.

Cast irons are obtained from iron ores in blast furnaces, and steel are obtained from steelmaking cast iron in open-hearth converters or electric furnaces.

Our country in reserves of iron ores occupies first place in world. Production of metals is growing from year to year at such a tempo as unknown in any capitalistic country. Control figures on development of People's economy of USSR for seven-year plan note high rate of growth of production of ferrous and nonferrous metals. In USSR in 1961 cast-iron production reached 51.5 million tons, that of steel 71.0 million tons. In 1965 was proposed the casting of 65-70 million tons of cast iron and 86-91 million tons of steel. According to directives of XXII congress of CPSU, in 1980 there should be smelted 250 million tons of steel.

§ 1. Components of Iron - Carbide Alloys

Components of iron-carbide alloys are iron and carbon. The purest iron obtained at present for technical purposes contains up to 0.15% impurities: sulfur, phosphorus, manganese, silicon, carbon, and others. This iron is called technical iron. For scientific purposes can be obtained iron of higher purity, containing total of 0.01% impurities.

Technical iron possesses specific gravity of 78.9 kN/m^3 (7.89 gf/cm^3) and

melting point of 1539°C. Iron pertains to number of metals resistant to atmospheric corrosion; in humid medium it corrodes.

Technical iron is characterized by good technological properties: it is easily forged, rolled in cold and hot states, has high ductility, and allows deep stamping. It welds well by gas and electric welding.

Technical iron possesses low ultimate strength [$\sigma_B = 250-300 \text{ MN/m}^2$ (25-30 kgf/mm^2)], low hardness [$HB = 500-700 \text{ MN/m}^2$ (50-70 kgf/mm^2)], and very high elongation per unit length ($\delta = 30-50\%$). Owing to low mechanical properties, technical iron in aircraft construction is not applied in practice.

Very important property of iron is polymorphism (allotropy). By thermal and X-ray diffraction analysis it has been established that iron has two modifications, differing from each other in crystal structure and properties. Let us trace

allotropic transformations of iron on curve of cooling (Fig. 7.1).

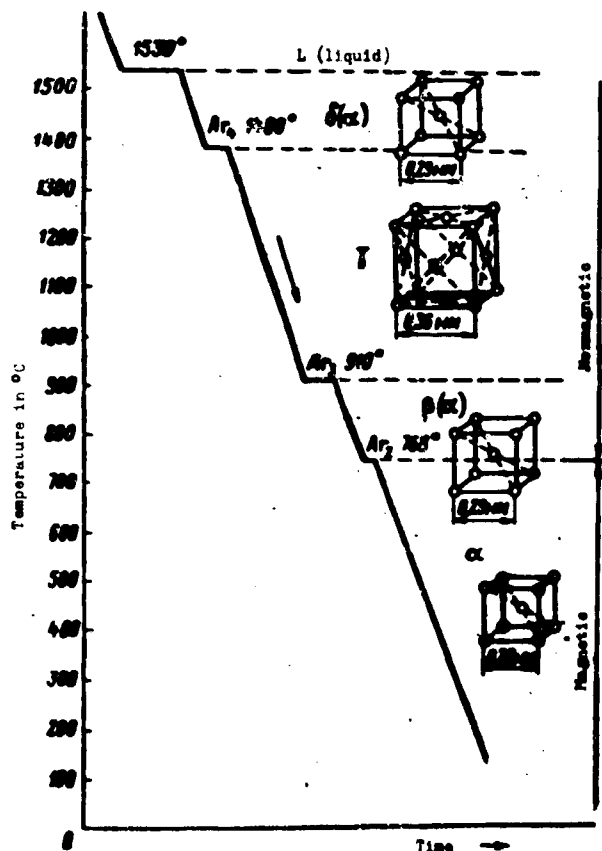


Fig. 7.1. Curve of cooling of iron.

Critical points of iron are designated by letter A, where during cooling to it is added letter r and during heating the letter c. For distinction of critical points from each other are introduced indices: "1," "2," "3," "4," i.e., during heating these are points Ac_1 , Ac_2 , Ac_3 , Ac_4 , and during cooling respectively Ar_1 , Ar_2 , Ar_3 , Ar_4 .

Stop on curves of cooling and heating is observed at temperature of 1539°C and corresponds to temperature of hardening and fusion of pure iron. After hardening iron is in the form of modification δ , having crystal structure of body-centered cube with lattice parameter equal to

0.29 Nm. Further cooling of iron to temperature of 1400°C (point Ar_4) leads to formation of new modification, γ -iron, having crystal structure of cube with centered

edges and lattice parameter equal to 0.36 Nm. Modification γ -iron exists to temperature of 910°C, at which it passes to nonmagnetic modification, δ -iron, with crystal lattice of body-centered cube and lattice parameter equal to 0.29 Nm. At temperature of 768°C (Curie point A_{r2}) nonmagnetic δ -iron passes to ferromagnetic α -iron, also having crystal structure of body-centered cube with lattice parameter equal to 0.28 Nm. Critical point A_{r1} or A_{c1} corresponds to temperature of 723°C; this transformation is accomplished only in alloys of iron with carbon; in pure iron it is absent.

Since α -, β -, and δ -iron have the same crystal lattice of body-centered cube, it is customarily considered that iron has only two modifications

to 910° and from 1400 to 1539°..... α -iron
from 910 to 1400°..... γ -iron

and not four as considered earlier.

When iron is heated from room temperature to melting point, transformations occur in reverse sequence. Here critical point of transformation $\alpha \rightarrow \beta$ is designated A_{c2} , $\beta \rightarrow \gamma$, A_{c3} , and $\gamma \rightarrow \delta$, A_{c4} .

The most important is transformation $\alpha \rightleftharpoons \gamma$ and connected change of properties, since at room temperatures in structure of steel is solid solution based on α -iron, and for majority of forms of hot technological processes heating is produced to structure of solid solution on the basis of γ -iron. Iron of α and γ types have various specific gravity, densities, magnetic, and other physical properties. Solubility of carbon in these modifications of iron also is different. Solubility of carbon in γ -iron exceeds by 100 times maximum solubility of carbon in α -iron, which is used during heat and chemical-heat treatment of steel.

Second component of iron-carbide alloys is carbon. Two of its modifications are known: diamond and graphite. In iron-carbide alloys carbon is present either in the form of graphite or in the form of chemical compound with iron Fe_3C .

§ 2. Structural Components of Iron - Carbide Alloys

Depending upon temperature and content of carbon, iron-carbide alloys can have following structural components: ferrite, cementite, austenite, perlite, ledeburite, and graphite.

Ferrite constitutes solid solution of introduction of carbon in α -iron.

Solubility of carbon in α -iron at normal temperature is 0.006%, and at 723°C is 0.02%. Therefore ferrite may be considered in practice pure iron. Ferrite has body-centered cubic lattice and is characterized by insignificant values of hardness and strength but high ductility.

$$[\sigma_B = 250 \text{ MN/m}^2 (25 \text{ kgf/mm}^2), \delta = 50\%, \text{HB} = 800 \text{ MN/m}^2 (80 \text{ kgf/mm}^2)].$$

Microstructure of ferrite is presented in Fig. 7.2a. To 768°C it is ferromagnet and above that paramagnetic.

Cementite constitutes chemical compound of iron with carbon, i.e., iron carbide Fe_3C . Cementite contains 6.67% carbon, is very hard, and is brittle ($\text{HB} \approx 8000 \text{ MN/m}^2$ [800 kgf/mm^2], a_H is close to zero). Cementite has complicated crystal lattice. To 210°C it is ferromagnet and above is paramagnetic. Cementite is present in structure of iron-carbide alloys in different forms: in steel in the form of lattice on grain boundaries (see Fig. 7.2b); in cast iron in the form of needles, in form of separate light bodies and grains (see Fig. 7.2c).

Austenite is solid solution of introduction of carbon in γ -iron.

Maximum concentration of carbon in austenite is 2.0% at 1130°C. With lowering of temperature solubility of carbon in austenite decreases, and at 723°C it attains 0.80%.

Austenite has face-centered cubic lattice. It is characterized by low strength, hardness, and high ductility [$\delta = 40\text{--}50\%$, $\text{HB} = 1600\text{--}2000 \text{ MN/m}^2$ ($160\text{--}200 \text{ kgf/mm}^2$)]. Austenite is paramagnetic. Its microstructure consists of light grains with characteristic double lines (see Fig. 7.2d).

Perlite is mechanical mixture of ferrite and cementite, the product of disintegration of slowly cooled austenite. Concentration of carbon in perlite is 0.8%. Temperature of formation of perlite is 723°C. Perlite can have laminar or granular structure if cementite has form of plates (see Fig. 7.2e) or grains (see Fig. 7.2f).

Mechanical properties of perlite depend on degree of fragmentation of particles of cementite - the bigger they are the lower the mechanical properties. For instance, laminar perlite has $\sigma_B = 820 \text{ MN/m}^2$ (82 kgf/mm^2), $\delta = 15\%$, $\text{HB} = 1900\text{--}2300 \text{ MN/m}^2$ ($190\text{--}230 \text{ kgf/mm}^2$), and for granular perlite $\sigma_B = 630 \text{ MN/m}^2$ (63 kgf/mm^2), $\delta = 20\%$, $\text{HB} = 1600\text{--}1900 \text{ MN/m}^2$ ($160\text{--}190 \text{ kgf/mm}^2$).

Ledeburite is mechanical mixture of austenite and cementite, formed during

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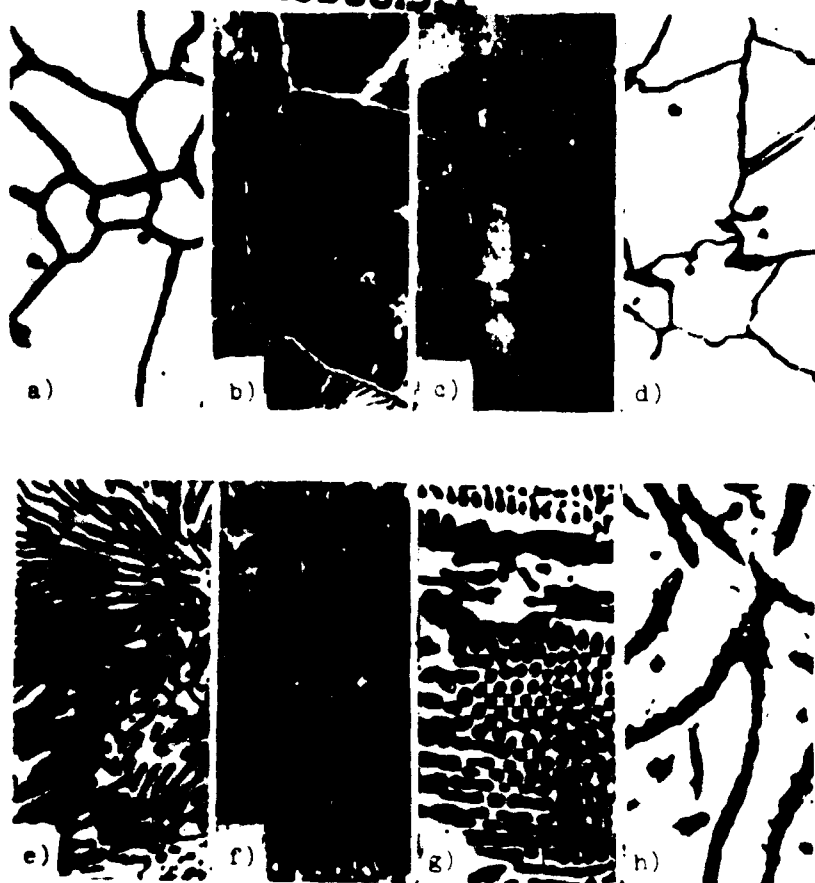


Fig. 7.2. Structural components of iron-carbide alloys.
a) ferrite, $\times 300$; b) thin light network of cementite against background of perlite, $\times 300$; c) ledeburite and light particles of cementite, $\times 300$; d) austenite $\times 250$; e) laminar perlite, $\times 300$; f) granular perlite, $\times 250$; g) ledeburite, $\times 250$; h) plate of graphite on light background of basic metal before etching, $\times 250$.

crystallization of liquid alloy containing 4.3% C. At 723°C austenite is turned into perlite. This transformation occurs also with austenite entering into composition of ledeburite. Thus below 723°C ledeburite no longer constitutes mixture of austenite with cementite but a mixture of perlite with cementite. In Fig. 7.2g is shown ledeburite, consisting of light cementite bases with dark round particles of perlite. Ledeburite is very hard [HB ≈ 400 (Vickers)] and brittle. It is present in structure of white cast iron.

Graphite constitutes free carbon disposed in basic mass of metal. It is present in structure of cast iron (see Fig. 7.2h) and can have form of plates, flakes, or spherical particles of black color.

Mechanical properties of iron-carbide alloys are changed depending upon quantity of structural components, their form, quantity, and location.

§ 3. Constitutional Diagram of Iron - Carbon System

Constitutional diagram of alloys of iron - carbon system is plotted as a result of works of many scientists. Responsible for diagram is D. K. Chernov, who in 1868 first established critical points in steel.

Since carbon and iron form chemical compound Fe_3C (cementite) or can be present in alloy in form of graphite, there exist two constitutional diagrams of alloys of iron and carbon: cementite and graphite. Cementite diagram, characterizing iron - cementite system, is metastable (since process of disintegration of Fe_3C is possible). Graphite diagram, characterizing iron - graphite system, is stable.

Let us consider constitutional diagram of iron - cementite, which has large practical value.

First, diagram makes it possible to study structure of iron - carbide alloys and to grasp complicated processes occurring during their heating and cooling.

Secondly, it permits one to select optimum conditions of heat treatment steels and cast irons and to determine temperature limits of treatment by pressure.

Along the axis of abscissas of diagram is plotted content of carbon from 0 to 6.67% (corresponding to content of carbon in cementite); along the axis of ordinates is plotted temperature.

Alloys of iron with content of more than 6.67% carbon are not of interest, since alloys applied in technology contain no more than 5-6% carbon.

For simplicity of consideration of diagram we shall not consider its upper left corner, characterizing formation of solid solution δ . In Fig. 7.3 is represented constitutional diagram of iron - carbide alloys.

On diagram are the following characteristic points and lines. Point A (1539°C , 0% C) equals crystallization temperature of pure iron. Point D ($\sim 1550^\circ\text{C}$, 6.67% C) equals crystallization temperature of cementite. Line ACD (liquidus) characterizes beginning of crystallization of all alloys. Above this line all alloys are in liquid state.

During cooling alloys containing up to 4.3% carbon start to harden along line AC, separating crystals of austenite. Alloys containing more than 4.3% carbon start to harden along line CD, separating crystals of primary cementite Fe_3C_I . At point C (1130°C , 4.3% C) occurs simultaneous crystallization from liquid alloy of austenite and cementite, forming eutectic - ledeburite.

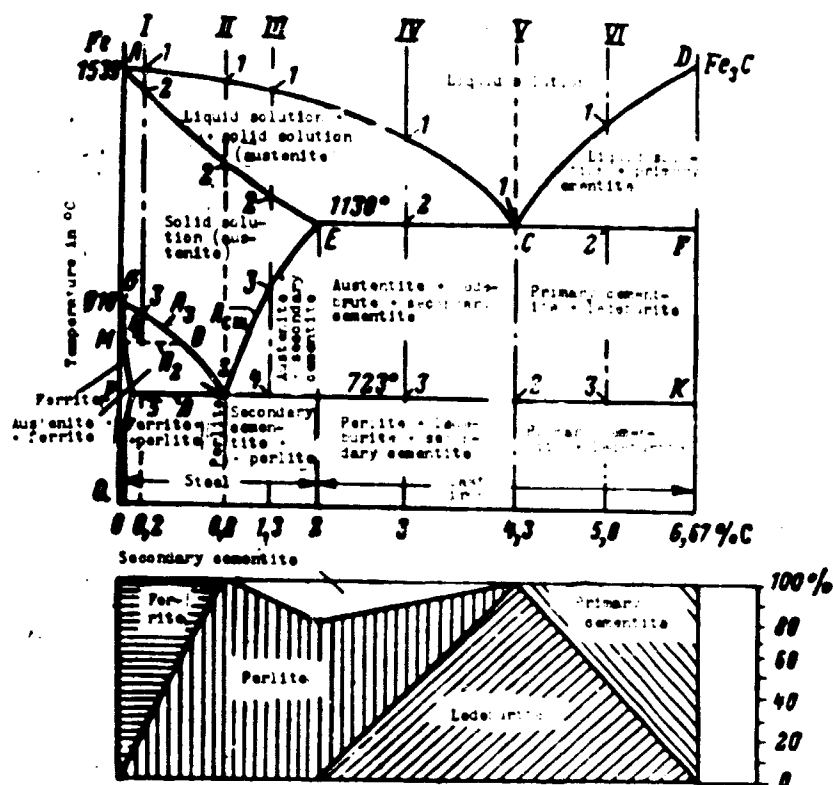


Fig. 7.3. Constitutional diagram of iron - carbon (cementite).

Point C is called eutectic point. Line AECF (solidus) characterizes end of crystallization of all alloys. Below this line all alloys are in solid state.

Point G (910°C, 0% C) characterizes allotropic transformation of iron $\alpha \rightleftharpoons \gamma$.

Line GOS characterizes beginning of transformation of austenite to ferrite.

Line GMP characterizes end of transition of austenite to ferrite.

Line SE characterizes beginning of singling out of secondary cementite from austenite. Line MO characterizes appearance of magnetic properties for ferrite. Point E (1130°C, 2% C) characterizes the biggest quantity of carbon which can be dissolved in γ -iron. Line PSK characterizes disintegration of austenite with concentration of 0.8% carbon to eutectoid mixture of ferrite with cementite - pearlite. Point S (723°C, 0.8% C) is called eutectoid or pearlitic point. Line PQ characterizes beginning of singling out of tertiary cementite from ferrite.

In Fig. 7.4 is given diagram of division of alloys per iron - carbon constitutional diagram.

Transformations in iron - carbide alloys are explained by two processes:

- 1) primary crystallization (transformation from liquid state to solid);

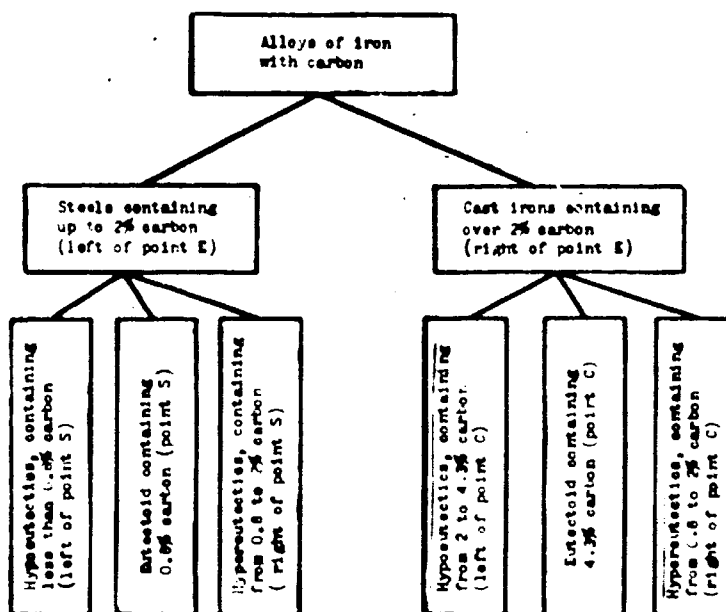


Fig. 7.4. Diagram of division of alloys per iron - carbon constitutional diagram.

2) secondary crystallization or recrystallization (transformation to solid state).

§ 4. Structures and Property Slowly Cooled Steels

For understanding mechanism of formation of structures of steel let us trace the process of slow cooling of hypoeutectoid, eutectoid, and hypereutectoid, steels.

Hypoeutectoid steel contains 0.2% carbon. Composition of this steel is marked on diagram by dotted line I (see Fig. 7.3). Above point 1, lying on liquidus, steel will be liquid. At point 1 starts crystallization of steel with formation of solid solution of austenite. At point 2, lying on solidus, crystallization of steel stops. During cooling, to point 3 no transformations in steel occur; it preserves structure of austenite.

Point 3 lies on line GOS, beginning of recrystallization of γ . At this temperature austenite, containing 0.2% carbon, begins to turn to ferrite. Temperature of transformation of alloys on line GOS for brevity is designated A_3 .

At point 4 at temperature of 768°C occurs magnetic transformation of ferrite: nonmagnetic ferrite becomes magnetic. Critical temperatures of transformation of alloys along line MO are designated A_2 .

With lowering of temperature from point 4 to point 5 ferrite is separated ever faster, and at the same time austenite is enriched by carbon along line GDS, striving to eutectoid composition (point S). Point S lies on line of eutectoid temperature of 723°C . Steel at this temperature consists of grains of ferrite and grains of austenite of eutectoid composition (0.8% carbon). At this temperature austenite disintegrates to ferrite-cementite mixture, i.e., to perlite. Below temperature of point 5 no transformations in steel occur and structure of this steel consists of grains of ferrite and perlite (Fig. 7.4 a).

Analogous transformations occur during slow cooling in all hypoeutectoid steels, but relationship between ferrite and perlite is changed. The more carbon in steel the more perlite and the less ferrite contained.

Eutectoid steel containing 0.8% carbon. Composition of this steels is marked on diagram by dotted line II (see Fig. 7.3).

At points 1 and 2 occur transformations of steel analogous to transformations of hypoeutectoid steel. As a result of hardening there forms austenite, stable to point 3. At point 3 (point S of diagram) occurs recrystallization of steel, as a result of which austenite is broken up completely into eutectoid mixture of ferrite and cementite, i.e., perlite. Below point S in steel no more transformations occur and it preserves structure of perlite to room temperature (see Fig. 7.5 b).



Fig. 7.5. Microstructures of slowly cooled carbon steels.
a) hypoeutectoid (0.2% C, $\times 250$); b) eutectoid (0.8% C, $\times 300$); c) hypereutectoid (1.1% C, $\times 300$).

Hypereutectoid steel containing 1.1% carbon. Composition of this steel is marked on diagram by dotted line III (see Fig. 7.3). At points 1 and 2 occur transformations analogous to transformations of eutectoid steels. At temperature

At point 3 starts crystallization of secondary cementite from austenite. Temperature of transformation along line SE is designated by A_{CT} . Separated cementite is disposed on boundaries of grains of austenite, forming network. Quantity of carbon in austenite between points 3 and 4 continuously decreases along line SE, striving to eutectoid composition (point S). At point 4 occurs disintegration of austenite to perlite. With further cooling of steel below 723°C no transformations occur. Final structure of hypereutectoid steels after slow cooling will consist of grains of perlite bordered by network of cementite (see Fig. 7.5c). Network of secondary cementite will be thicker the more carbon in steel (see Fig. 7.3).

§ 5. Structure and Properties of Slowly Cooled Cast Iron

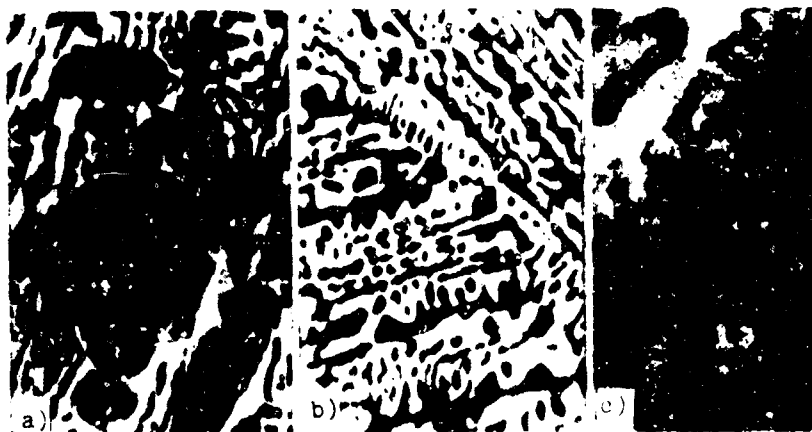
For understanding mechanism of formation of structures of cast iron let us trace process of slow cooling of hypoeutectic, eutectic, and hypereutectic cast iron.

Hypoeutectic cast iron containing 3% carbon. Composition of this cast iron is marked on diagram by dotted line IV (see Fig. 7.3). Crystallization of alloy starts at point 1 with formation of crystals of austenite, quantity of which is increased with cooling of alloy. During cooling between points 1 and 2, concentration of carbon in liquid alloy is increased to eutectic composition of 4.3% (point C). At point 2 at a temperature of 1130°C occurs final hardening of cast iron. Here, remaining quantity of liquid alloy is turned into eutectic mixture - ledeburite. Ledeburite consists of crystals of austenite containing 2% carbon and crystals of cementite. Below point 2 structure of alloy consists of austenite and ledeburite. With further lowering of temperature, owing to decreasing solubility of carbon in austenite, secondary cementite is separated, quantity of which is increased with lowering of temperature. At point 3 at temperature of 723°C remaining austenite with concentration of 0.8% C (corresponding to point S) is broken up into perlite.

Thus, structure of hypoeutectic cast iron after slow cooling consists of perlite, secondary cementite, and sections of ledeburite (Fig. 7.6a). Ledeburite at room temperature consists of cementite and disintegrating austenite (perlite).

Eutectic cast iron containing 4.3% carbon. Composition of this alloy is marked on diagram by dotted line V (see Fig. 7.3). At point 1 liquid alloy at a temperature of 1130°C (point C) hardens completely with formation of eutectic - ledeburite. Between points 1 and 2 from austenite entering in composition of ledeburite

is separated secondary cementite. Here, concentration of carbon in austenite decreases to 0.8% (in accordance with line EC). At point 2 at a temperature of 723°C austenite entering in composition of ledeburite is turned into perlite. Below point 2 eutectic cast iron consists of ledeburite and secondary cementite (see Fig. 7.6b).



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Fig. 7.6. Microstructure of white cast iron, $\times 250$. a) hypoeutectic (3.0% C), b) eutectic (4.3% C), c) hypereutectic (5.0% C).

Hypereutectic cast iron containing 5% carbon. Composition of this alloy is marked on diagram by dotted line VI (see Fig. 7.3). At point 1 starts crystallization of cementite (for distinction from cementite separated from austenite along the line SE it is called primary). Between points 1 and 2 crystals of cementite grow and liquid cast iron is impoverished of carbon to eutectic composition (4.3% C).

At point 2 (1130°C) occurs full hardening of cast iron with formation of eutectic - ledeburite. After hardening, structure of hypereutectic cast iron consists of crystals of primary cementite and ledeburite. Further, between points 2 and 3 occurs singling out of secondary cementite from austenite entering in composition ledeburite. At point 3 (723°C) this austenite is turned into perlite. Thus structure of hypereutectic cast iron consists of primary cementite and ledeburite (see Fig. 7.6c).

CHAPTER VIII

HEAT TREATMENT OF STEEL

Heat treatment is technological process of hot processing of metals and alloys as a result of which occurs change of internal structure of mechanical, physical and physicochemical properties.

Heat treatment depends on temperature of heating, duration of holding at given temperature, rate of heating, and rate of cooling. By changing these parameters it is possible with the same chemical composition of alloy to obtain different structure, and this means different properties. Therefore heat treatment is widespread and important technological process for improvement of exploitational characteristics of majority of parts and tools.

Basic forms of heat treatment steel are: annealing, normalization, hardening, tempering.

Annealing and normalization pertain to preliminary heat treatment and hardening and tempering - to final heat treatment. Purpose of preliminary heat treatment consists of crushing of grain of steel, destruction of internal stresses, increase of ductility, and lowering of hardness. To preliminary heat treatment are subjected half-finished products (stampings, forgings, and so forth) for improvement of workability in process of manufacture of part. To final heat treatment are subjected finished parts and tools for imparting to them required properties, depending upon conditions of work.

§ 1. Bases of Heat Treatment of Steel

Heat treatment of steel is based on phenomena of recrystallization (secondary crystallization), occurring at temperatures corresponding to lines $GOS (A_3)$, $Se (A_{CT})$

and PSK (A_1) of iron - carbon constitutional diagram. Obligatory for all forms of heat treatment are heating of alloy to defined temperature, holding at this temperature, and subsequent cooling at defined rate.

Transformations in steel during heating. Heating of steel and holding at given temperature, which are done during heat treatment, in most cases are for the purpose of obtaining structure of austenite. Before heating hypoeutectoid steels have structure of perlite and ferrite, eutectoid steels have that of perlite, and hypereutectoid steels have that of perlite and cementite. During heating of these steels to temperatures not exceeding 723°C (line PSK, point Ac_1 , see Fig. 7.2), in their structure no changes occur. During heating above point Ac_1 in steel occurs perlitic-austenitic transformation. This transformation consists of several simultaneously occurring processes: allotropic transformation of α -iron to γ -iron, dissolution of cementite to austenite, and diffusion of ions of carbon from cementite to austenite, and diffusion of ions of carbon from cementite grains in depth of austenite.

With further increase of temperature in eutectoid steel no changes occur and structure of steel constitutes solid solution - austenite.

With increase of temperature of heating to point Ac_3 , in hypoeutectoid steels occurs process of transformation of ferrite to austenite, and in hypereutectoid steels to point A_{CT} takes place process of dissolution of secondary cementite to austenite. Upon achievement of shown temperatures process of transformation of ferrite to austenite and process of dissolution of cementite in austenite are completed.

After that, in steel takes place diffusion process of levelling of chemical composition of austenite, caused by different concentration of carbon both in separate grains and between grains.

For production of uniform austenite there is needed holding for defined time at these temperatures.

The process of transformation during heat treatment is influenced by temperature of heating and composition of steel. The more the temperature of steel is above critical level the less time necessary for completion of process. Increase of content of carbon in steel leads to acceleration of transformation.

After termination of transformations, steel obtains fine-grained structure.

Increase of temperature of heating above that shown or increase of time of holding can lead to unnecessary growth of grains of austenite. This phenomenon is undesirable, since grain size of austenite renders large influence on behavior of steel during heat treatment and mechanical properties obtained after it.

Increase of dimension of grain during heating occurs differently for different steels. We distinguish real and hereditary grains of austenite. Grain which is obtained as a result of given heating and which is observed directly under microscope is called real. Dimension of real grain depends on temperature of heating of steel. By hereditary grain is understood inclination of austenite to grain growth. Steel in which growth of grain starts with slight overheating above critical points are called hereditary coarse-grained. Steels in which grain growth starts only at considerable overheating above critical points are called hereditary fine-grained. Since size of real grain is determined mainly by temperature of heating and not size of natural grain, by changing conditions of heat treatment it is possible to correct initial coarse grain of steel. Grain size in steel is determined under microscope with magnification of 100 by means of comparison of grains visible on slide with standard dimensions. These dimensions are shown in Fig. 8.1, where figures 1, 2, 3, etc. signify number of grain. Steels with numbers 1-5 belong to coarse-grained

group, those with numbers 6-8 are fine-grained. Size of real grain of austenite affects certain properties of steel. The finer the grain of austenite the greater the impact toughness of steel, the less the hardenability, the worse the machinability and others.

Hardness, ultimate strength, yield point, elongation per unit length, and certain other properties of steel almost do not depend on grain size of austenite.

Size of hereditary grain determines technological process of treatment of steel. Hereditary coarse-grained steel is more sensitive to overheating than steel hereditary fine-grained.

Structures and properties of fast-cooled steels.

During cooling of steel from region of austenite there

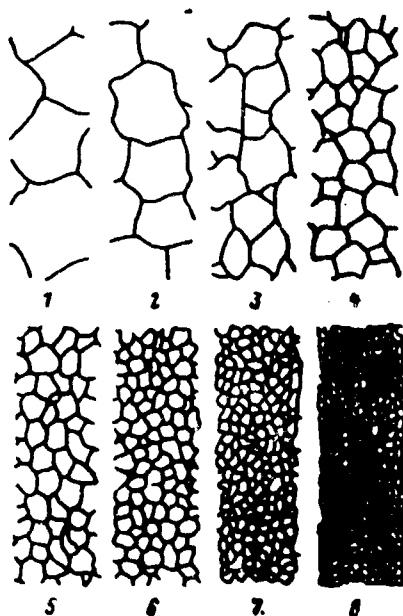


Fig. 8.1. Standard scale for appraisal of size grain of steel, $\times 100$.

occurs allotropic transformation of γ -iron to α -iron and disintegration of austenite.

Slow cooling of carbon steels causes disintegration of austenite with formation of ferrite-cementite mixture. This transformation consists of two stages: allotropic transformation of $\gamma \rightarrow \alpha$ and diffusion of atoms of carbon with formation of cementite. Reconstruction of γ -lattice to α -lattice occurs instantaneously. Formation of plates of cementite occurs gradually: in the beginning are formed small particles of cementite, which then are increased and are turned into larger particles. Structures and corresponding properties of steel obtained here correspond to equilibrium state.

If, however, rate of cooling of steel is increased, temperature of austenitic-perlitic transformation drops more the higher the rate of cooling. Here are formed products of disintegration of austenite, differing in nature and properties from those which appear during slow cooling.

Depending upon rate of cooling of austenite, there forms one (or combination) of the following structures: martensite, troostite, sorbite (Fig. 8.2). Formation

of these structures leads steel to unbalanced state and changes its properties.

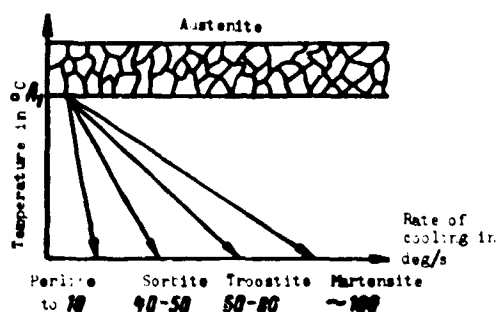


Fig. 8.2. Influence of rate of cooling on structure of steel.

Martensite - initial stage of disintegration of austenite - constitutes solid solution of carbon in α -iron. This structure can be obtained in steel during its cooling at rate of 180°C and more per second (see Fig.

8.2). Martensite contains as much carbon as was contained in initial austenite. Trans-

formation of austenite to martensite leads only to change of form of lattice of solid solution, without its disintegration. At higher rates of cooling of austenite crystal lattice of γ -iron is reconstructed to crystal lattice of α -iron but carbon does not succeed in emerging from it. Carbon in lattice of α -iron in the same quantity as in initial austenite strongly distorts it, since α -iron in practice does not dissolve carbon. Therefore martensite possesses raised strength, hardness, and brittleness. Martensite is magnet and is distinguished by acicular structure (Fig. 8.3a). By nature it is unstable and capable of spontaneous disintegration, especially at raised temperatures.

Martensite has not cubic lattice, like α -iron, but tetragonal (Fig. 8.4a). This lattice can be obtained from that of α -iron if in one direction cubic cells are compressed and in the other are expanded. Degree of tetragonality of lattice, measured by ratio of height of cell to length of one of sides of base (c/a), is

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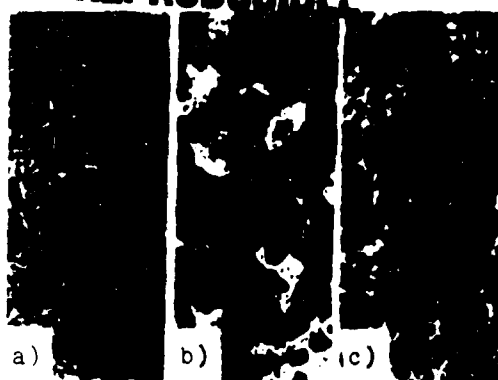


Fig. 8.3. Structures of fast-cooled steels, $\times 300$. a) martensite; b) martensite + troostite (dark); c) sorbite.

greater than unity. Degree of tetragonality of martensite increases with increase of content of carbon in steel (see Fig. 8.4b).

Troostite - further stage of disintegration of austenite beyond martensite - constitutes mixture of ferrite and cementite of very high fineness (see Fig. 8.3b). This structure can be obtained during cooling steel at rate of $60-80^{\circ}\text{C}$ per sec (see Fig. 8.2). Besides this, troostite structure can be obtained as a result of disintegration of martensite during its

heating to temperature of $400-500^{\circ}\text{C}$. Troostite possesses lower hardness and higher toughness than martensite. Troostite also is unstable and capable under certain conditions of disintegration.

Sorbite - following stage, after troostite, of disintegration of austenite - constitutes fine-grained mixture of ferrite and cementite (see Fig. 8.3c). This structure can be obtained during cooling of steel at rate of $40-50^{\circ}\text{C}$ per sec (see Fig. 8.2). Besides this, sorbite structure can be obtained as a result of disintegration of martensite or troostite during their heating to temperatures of $550-650^{\circ}\text{C}$. Sorbite in equilibrium state is close to perlite but has larger degree of crushing of particles. Sorbite has hardness close to that of perlite but is tougher and more elastic.

Consequently, perlite, sorbite, and troostite are mixtures of ferrite and cementite and differ from each other only in degree of crushing of cementite. Process of their formation is diffusion. Sorbite and troostite, in distinction from perlite, do not have constant chemical composition and are formed in steel with different content of carbon. Structure of martensite constitutes solid solution of carbon in α -iron, and process of its formation bears diffusionless character. Sorbite, troostite, and martensite structures obtained at rates of cooling, in distinction from perlite, are called unbalanced - unstable. With heating to certain temperatures below critical there occurs transition of martensite to troostite and further to sorbite.

Various structure brings about various properties of structures of steel. In Fig. 8.5 are given curves of change of ultimate strength, HB hardness, and elongation

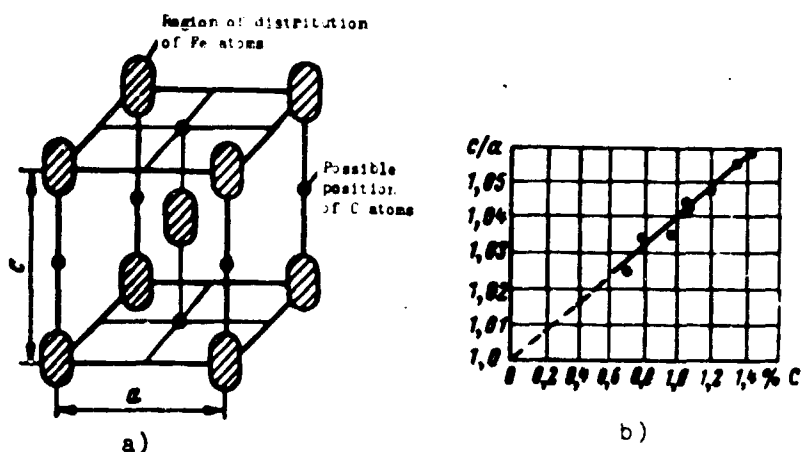


Fig. 8.4. Crystal structure of martensite (a) and dependence of tetragonality of martensite on carbon content (b).

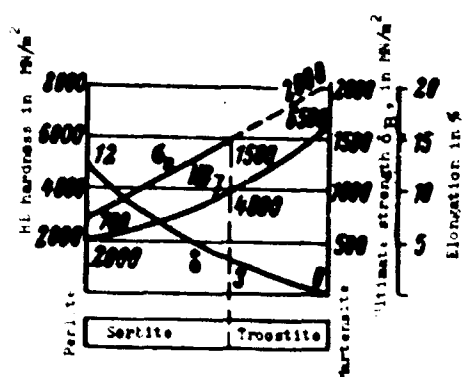


Fig. 8.5. Diagram of change of mechanical properties of eutectoid steels in different states from pearlite to martensite.

per unit length δ of eutectoid steels in different states from pearlite to martensite. From diagram one may see that properties of sorbite and troostite are midway between properties of pearlite and martensite. Properties of structures of hypoeutectoid and hypereutectoid steels differ from properties of the same structures of eutectoid steels depending upon carbon content.

Transformation of austenite during continuous

cooling. Cooling of steel is the most important stage of heat treatment. Rate of cooling of steel to state of austenite determines obtaining of one or another structure of disintegration of austenite,

and this means imparting of defined properties to steel.

If steel heated to state of austenite is cooled with increasing rate, this will entail cooling of austenite. The higher the rate of cooling the greater the cooling of austenite. From iron - carbon constitutional diagram it follows that austenite is stable only at temperatures above point A_{c1} (for eutectoid steel). With cooling of austenite below point A_{r1} its disintegration occurs. With increase of rate of cooling point A_{r1} is lowered continuously (Fig. 8.6). Lowered critical point A_{r1} is designated A_{r1}' . The lower the temperature of critical point A_{r1} the greater the

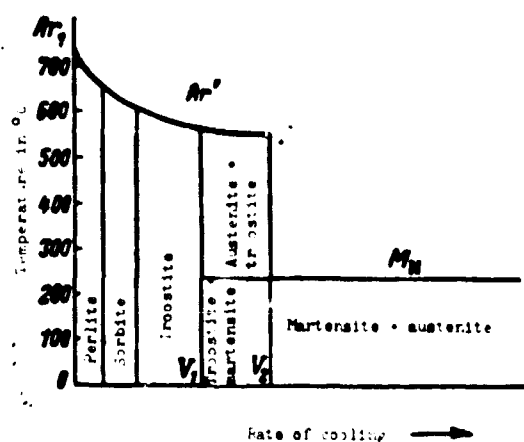


Fig. 8.6. Transformations of austenite during continuous cooling.

crushing of products of disintegration of austenite and the higher their hardness.

At low rate of cooling transformation of austenite will occur at temperature of the order of 700°C. Product of transformation will be perlite of coarse structure, possessing low hardness. At high rate of cooling transformation occurs at lower temperature, of the order of 650-600°C, structure of perlite becomes finer (sorbite forms), and hardness increases. With further acceleration

of cooling temperatures of transformation are lowered ever more and in interval of temperatures from 600 to 500°C there forms structure of troostite, possessing high hardness. With rate of cooling V_1 , on diagram along with point Ar' appears second point, which is point of beginning martensite transformation and is designated, in distinction from first point, Ar'' (M_H). Here, martensite forms. Both these critical points exist up to rate of cooling V_2 . For rate of cooling from V_1 to V_2 along with troostite is observed martensite (troostite-martensite structure). With further increase of rate of cooling point Ar' disappears. With rate higher than V_2 from austenite there forms only martensite. Minimum rate of cooling at which only martensite forms is called critical rate of hardening V_{kp} .

As follows from diagram (Fig. 8.6), formation from austenite of martensite is characterized by horizontal line, i.e., martensite, in contrast to perlite, sorbite, and troostite, forms not at various temperatures but always at the same temperature of rate of cooling from a temperature above critical.

At a temperature corresponding to critical point M_H occurs only the beginning of formation of martensite from austenite.

Further more full transformation of austenite to martensite occurs with decrease of temperature and is finished at defined temperature, which is designated M_K . Thus, process of formation of martensite from austenite takes place in interval of temperatures from M_H to M_K .

Position of points M_H and M_K is determined by chemical composition of steel and in the first place by carbon content. The more carbon in steel (Fig. 8.7) the

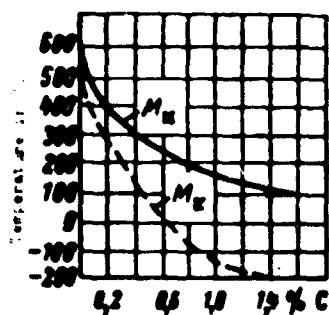


Fig. 8.7. Dependence of martensite points M_H and M_K on carbon content in steel.

lower the position of martensite points M_H and M_K . In high-carbon steels containing carbon more than 0.6% martensite transformation is finished at temperatures lower than zero. The lower the temperature of martensite points the more residual austenite is obtained. Residual austenite is austenite not transformed to martensite. Therefore in order to obtain in high-carbon steels more martensite it is necessary to cool them to temperatures lower than zero.

Transformation of austenite at constant temperature (isothermal transformation). It has been established

that rate and character of disintegration of austenite depend on degree of its cooling. Austenite, depending upon to what temperature it is cooled, behaves differently: its stability is changed, i.e., time to beginning of its disintegration, speed of process of disintegration is changed, and character of transformation changes, i.e., products of disintegration. These peculiarities of transformation of austenite depending upon temperature of its cooling are characterized graphically by diagram of isothermal disintegration of austenite.

In Fig. 8.8 is given diagram of isothermal disintegration of austenite of eutectoid carbon steel. Diagram is plotted on semilogarithmic temperature - time coordinates.

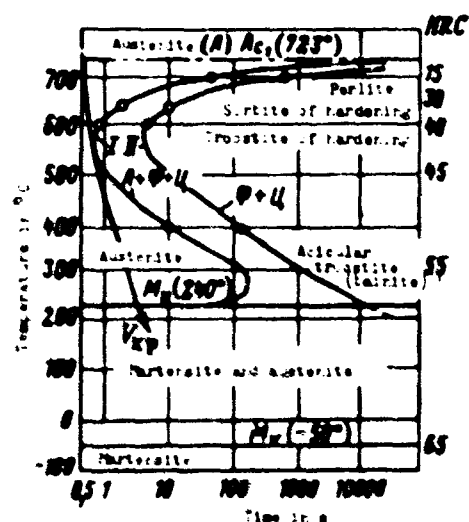


Fig. 8.8. Diagram of isothermal disintegration of austenite of eutectoid carbon steel (0.8% C).

On vertical axis is plotted temperature of cooling of austenite, i.e., that temperature to which austenite remains without disintegration. On horizontal axis is plotted time in logarithmic scale, which makes it possible to trace transformations occurring during interval of time from fractions of a second to days and more.

Curves on diagram were plotted as follows. Steel of defined composition is heated to region of uniform austenite and then fast-cooled, for instance, to 700°C. Then steel is held at this temperature for time sufficient for full

disintegration of austenite. Here, on diagram are plotted points corresponding to beginning and end of transformation of austenite at given temperature. Besides this, observations are made of changes in structure of steel. In precisely the same manner steel is cooled and held at other temperatures: 600, 500, 400, 300, 200, and 100°C.

Diagram of isothermal transformation consists of following lines (see Fig. 8.8). Upper dotted line is boundary of austenitic state. Above this line steel has structure of austenite. Austenite, as it is known, at a temperature higher than 723°C is stable, disintegration starts below this temperature, but during fast cooling, being undercooled, it can exist for certain interval of time without disintegrating. This time is called latent (incubative) period.

Two curves having form of Russian letter C characterize beginning (I curve) and end (II curve) of disintegration of austenite.

Segment from vertical axis to curve I characterizes stability of austenite in time (incubative period). As can be seen in Fig. 8.8, at temperatures of 500-600°C this segment has minimum dimensions, and consequently stability of austenite at these temperatures is least. Conversely, at 650-700°C and 250-300°C this segment has maximum dimensions, and consequently stability of austenite is the greatest.

Between curves I and II simultaneously exist austenite and products of its disintegration; to the right of curve II are only products of disintegration of austenite.

Depending upon temperature to which austenite is cooled, some or other structures of disintegration are obtained.

At high temperatures of isothermal transformation (650-700°C) final structure of disintegration is perlite, lower (600-650°C) sorbite, still lower (500-600°C) troostite, and at lower temperatures (250-450°C) acicular troostite or bainite. Acicular troostite is a mechanical mixture of ferrite and cementite of greater fineness than troostite, the ferrite in circular troostite being supersaturated by carbon. Besides this, during its formation are also present elements of martensite transformation.

In lower part of diagram are two horizontal lines - beginning (M_H) and end (M_K) of martensite transformation.

Formation of martensite begins only when austenite is cooled below line M_H (240°C). Transformation of austenite to martensite below temperature of line M_K is

diffusionless process. Full disintegration of austenite is possible only upon achievement of temperature of line M_H ($-50^\circ C$) for given steel. Otherwise, in structure of steel remains part of undecomposed (residual) austenite, which lowers hardness.

Transformation of austenite is conveniently considered if one combines curves of cooling with diagram of isothermal disintegration of austenite.

As can be seen from diagram (Fig. 8.7), large influence on structure of products of disintegration of austenite is rendered by rate of cooling. For low rate curve of cooling V_1 intersects diagram of isothermal disintegration in region of high temperatures, and product of transformation is perlite. With higher rate curve of cooling V_2 intersects diagram of isothermal disintegration at lower temperatures and product of transformation is sorbite. With further increase of rate of cooling to V_3 temperature of transformation is lowered still more and structure of troostite is formed.

Curve V_4 shows partial transformation to troostite (section ab) and partial transformation to martensite (below M_H). Curve of cooling V_5 , depicted tangent to

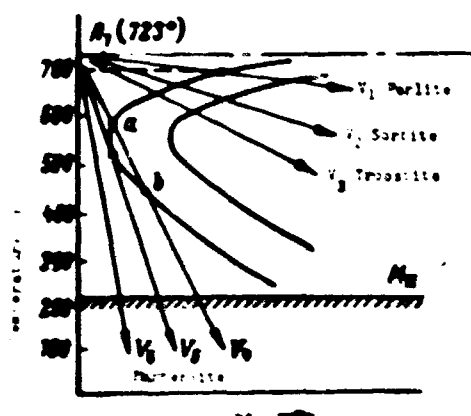


Fig. 8.7. Combination of curves of cooling with diagram of isothermal disintegration of austenite.

decay curve, is critical rate of hardening. This is minimum rate of cooling for which disintegration of austenite up to martensite point M_H does not occur. As a result of transformation, martensite forms. Therefore for transformation of austenite to martensite it is necessary to cool steel at a rate not below critical (for instance, at rate V_5).

Perrite-cementite mixtures (perlite, sorbite, troostite,) may be obtained both during continuous cooling and during isothermal disintegration, and martensite can be obtained only

during continuous cooling. Fast cooling during hardening to martensite is necessary in order to pass through section of least stability of austenite without its disintegration to ferrite-cementite mixture.

Diagrams of isothermal transformation at present are plotted for many grades of steel and make it possible to designate exact conditions of such isothermal treatment

for which disintegration of austenite occurs in desirable direction.

Transformations during tempering. As it was shown, structure of steel after fast cooling at rate above critical (after hardening) consists of martensite and residual austenite and is unstable. Investigations have established that during heating of hardened steels to temperatures below critical (tempering) there occurs disintegration of unstable structure and formation of more equilibrium (stable) structures.

During tempering of hardened steels four transformations are observed.

First transformation occurs with heating to 80-170°C. It consists of decrease in degree of tetragonality of crystal lattice of martensite. Structure obtained here is called martensite of tempering. Decrease of tetragonality of tempered martensite is explained by singling out from oversaturated solid solution of this plates of cementite of several atomic layers in thickness. Martensite, owing to this, becomes low-carbon with smaller degree of distortion of crystal lattice. Plates of cementite are no longer isolated from lattice of solid solution and have common layer of atoms boundary with it. Microstructure of martensite of tempering has acicular structure but darker color than martensite of hardening.

Second transformation in steel takes place during heating to 200-300°C. It consists in that residual austenite is turned into tempered martensite. Besides this, there continues further disintegration of martensite accompanied by decrease in degree of tetragonality.

Third transformation at temperatures from 300 to 400°C is characterized by full disintegration of martensite to very fine ferrite-cementite mixture. Removal of considerable part of distortions of lattice and internal stresses is observed.

Fourth transformation at temperatures from 400 to 723°C consists in enlargement of particles of cementite (coagulation). Along with this is observed rounding of particles of cementite (spheroidization). Here distortions of crystal lattice of ferrite and internal stresses are removed completely.

In Fig. 8.10 presented diagram of transformations in steel during tempering. As a result of these transformations, hardened steel heated to 80-170°C obtains structure of martensite of tempering (Fig. 8.11a), that heated to 350-450°C takes on structure of troostite of tempering (see Fig. 8.11b), and that heated to 500-600°C takes on structure of sorbite of tempering (see Fig. 8.11c).

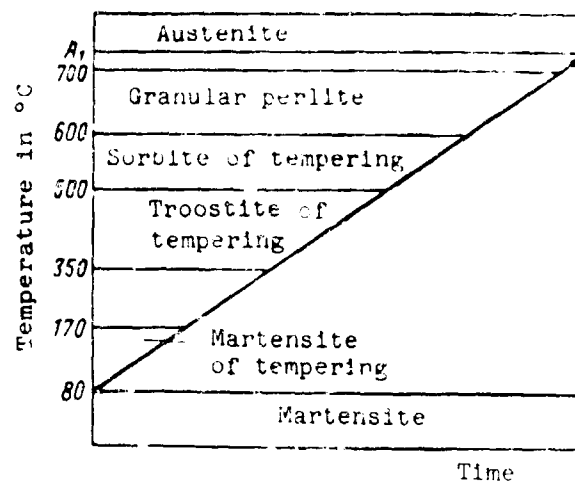
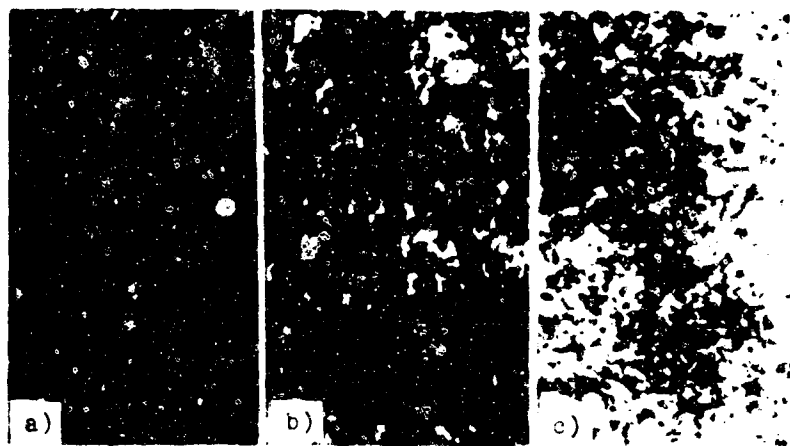


Fig. 8.10. Transformations in steel during tempering.



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Fig. 8.11. Microstructures of hardened carbon steel after tempering. a) Martensite; b) troostite; c) sorbite.

Increase of temperature of tempering above 650°C leads to further enlargement of particles of cementite and formation of structure of granular perlite.

Structures of tempering differ somewhat from corresponding structures of hardening: with those same characteristics of hardness they possess best indices of toughness and ductility. Such change of properties of tempered structures is due to peculiarity of their structure: sorbite and troostite of tempering have granular structure of cementite, sorbite and troostite of hardening are lamellar.

§ 2. Preliminary Heat Treatment of Steel

Steel billets, as a result of nonuniform cooling, after casting, rolling, forging, etc., take on heterogeneity of structure and properties, and internal

stresses in them appear.

For production fine-grained structure, elimination of chemical and structural heterogeneity, decrease of internal stresses, lowering of hardness of steel for the purpose of facilitating its machining, preliminary heat treatment is applied – annealing or normalizing. In certain cases normalization is operation of final heat treatment.

Annealing of Steel

Annealing is heat treatment consisting of heating steel to defined temperatures, holding, and subsequent slow cooling. Purposes of annealing are quite varied, as are conditions of its fulfillment. There exist different forms of annealing: full, incomplete, isothermal, spheroidizing, diffusion, and recrystallization.

Full annealing consists of heating steel to 30–50°C above line GS, holding at this temperature, and subsequent slow cooling (Fig. 8.12). Full annealing is connected with phase recrystallization and crushing of grains for hypoeutectoid steels at point A_{c3} and for eutectoid steels at point A_{c1} . Full annealing of steel

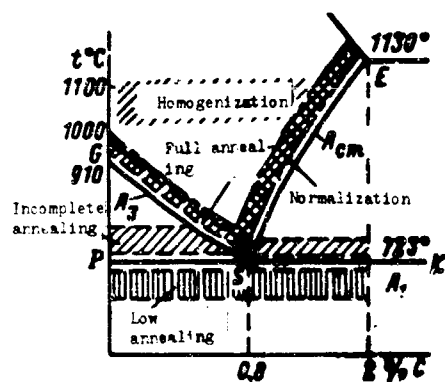


Fig. 8.12. Diagram of temperatures of heating of carbon steel for different forms of annealing.

is applied for the purpose of obtaining uniform fine-grained structure and also for reduction of hardness and increase of ductility. Basically subjected to this form of annealing are steels slated for machining.

Incomplete annealing consists of heating steel to 30–50°C above line PSK, holding at this temperature, and subsequent slow cooling (Fig. 8.12).

Incomplete annealing is connected also with partial recrystallization of steel at point A_{c1} . Excess structural components do not pass completely into solid solution (ferrite in hypoeutectoid, and cementite in hypereutectoid steels).

Incomplete (accelerated) annealing is used for removal of internal stresses and creation of fine-grained structure of hypoeutectoid steels with improved mechanical workability.

Isothermal annealing. For isothermal annealing (Fig. 8.13) part is heated to 30–50°C above line GSK, held at this temperature, and then rapidly transferred

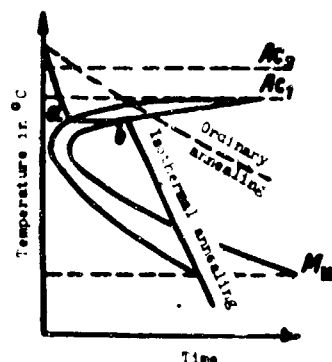


Fig. 8.13. Diagram of ordinary and isothermal annealing.

to medium having constant temperature somewhat below line PSK (point Ac_1), 630-700°C. At this constant temperature steel is held to full disintegration of austenite, after which it is air-cooled (hence the name isothermal annealing, i.e., annealing at constant temperature). During isothermal annealing transformation of austenite is accomplished not through cooling over defined temperature interval but at constant to temperature. Therefore this form of annealing gives more uniform structure.

Disintegration of austenite during isothermal annealing takes place just as disintegration during slow cooling.

After isothermal annealing steels have mechanical properties analogous to properties after full annealing. Basic advantage of isothermal annealing is that it completely removes residual stresses in steel. Besides this, isothermal annealing permits reducing time of annealing as compared to usual amount by almost twice. To isothermal annealing are subjected basically alloy steels.

Spheroidizing annealing (annealing to granular perlite). As a result of carrying out of full and incomplete annealing laminar perlite is obtained (inclusions of cementite in the form of plates). For production of granular perlite (inclusions of cementite in the form of grains) spheroidizing annealing is applied. Annealing to granular perlite consists of heating steel to temperature somewhat above line PSK (point Ac_1), prolonged holding (5-6 hours), and subsequent slow cooling. As a result of such operation laminar form of cementite is turned into granular.

Steel with structure of granular perlite has higher ductility, less hardness, and less strength than steel subjected to ordinary annealing. Spheroidizing annealing is used for hypereutectoid steels for the purpose of improvement of machinability.

Diffusion annealing (homogenization) consists of heating steel to 1000-1150°C (see Fig. 8.12), prolonged holding (10-15 hours) at this temperature, and subsequent slow cooling. As a result of diffusion annealing, there occurs levelling of heterogeneity of steel in chemical composition and decrease of liquation. To homogenization are subjected ingots of alloy steel, heavy steel castings, and others. High temperature of heating and prolonged holding lead to coarse-grained structure. This defect is removed in process of subsequent hot pressure working or

through application of full annealing to small grains.

Recrystallization (low) annealing consists of heating steel to temperature 50-100°C below line PSK (but above temperature of recrystallization), holding at this temperature, and subsequent cooling in air (Fig. 8.12). Recrystallizational annealing is applied for the purpose of removal of work hardening and internal stresses in steel after cold pressure treatment (rolling, drawing, or stamping). Besides this, it is possible to apply both intermediate annealing for increase of ductility and prevention of appearance of cracks in steel during its cold pressure treatment.

As a result of recrystallizational annealing, there forms uniform fine-grained structure with low hardness and maximum toughness.

After being annealed, steel displays structure corresponding to iron-carbon constitutional, i.e., for hypoeutectoid steels perlite and ferrite, for eutectoid steels perlite, for hypereutectoid steels perlite and cementite.

Normalization of Steel

Normalization is heat treatment consisting of heating steel to 30-50°C above line GSE, holding at this temperature and subsequent cooling in air (Fig. 8.12).

Normalization is used for correction of structure of overheated steels and hot-deformed billets, for removal of cementite lattice of hypereutectoid steels, and for levelling of structure of welded seam. After normalization, steel takes on more fine-grained structure than after annealing.

Depending upon carbon content in steel, structure and mechanical properties vary after normalization. For low-carbon steels (to 0.3%C) structure is perlite-ferrite and for medium-carbon and low-alloy steels structure is sorbite perlite or sorbite and structurally free ferrite.

For medium-carbon steels (0.3-0.5% C) distinction in properties of annealed and normalized steels is more considerable, since during normalization there is obtained sorbite-like perlite or sorbite with free ferrite with higher hardness and strength than obtained through annealing. Thus, normalized steel possesses higher hardness and lower toughness than annealed.

Normalization, being more a economical thermal process than annealing, has almost completely replaced annealing of low-carbon steels.

Conditions of Preliminary Heat Treatment

Selection of variant of preliminary heat treatment is determined by composition of steel and technological process to which parts or half-finished products are subjected.

For levelling of chemical composition of ingots or heavy castings is applied diffusion annealing. For lowering of hardness of steel after hot working, for the purpose of facilitating machining, full or incomplete annealing is chosen (depending upon composition of steel). After cold pressure treatment, for removal of work hardening and internal stresses, parts are subject to recrystallizational annealing.

Result of annealing and normalization is influenced by temperature and rate of heating, duration of holding, and rate of cooling.

Temperature of heating is selected from iron - carbon constitutional diagram depending upon carbon content in steel.

Rate of heating obtains especially large value when massive articles are heated, since in this case difference in temperature of internal and external parts of article increases. Articles of complicated form should also be subjected to slower heating.

During selection of rate of heating one should consider chemical composition of steel. The more carbon in steel the lower its thermal conductivity. Thermal conductivity decreases especially sharply with alloy steel. And the less the thermal conductivity of steel the slower must be its heating to avoid appearance of internal stresses and formation of cracks. Therefore it is impossible to indicate general rule for selection of rate of heating useful for all grades of steel. Duration of heating of steels during annealing and normalization is approximately 30-90 minutes per 25 mm of thickness of article.

Holding after heating to assigned temperature should ensure heating of all article and full completion of all processes accomplished in steel during its heating. Time of holding depends on thickness of article, initial structure, and chemical composition of steel. The more massive the article, the larger the grain of initial structure, the more prolonged must be holding. In practice holding is allotted 20-25% of duration of heating. To more prolonged holding is subjected steel during annealing to granular perlite (6-10 hours) and during diffusion annealing (10-15 hours).

Cooling after heating and holding should be of such duration that disintegration of solid solution can occur completely. Rate of cooling depends on cooling medium and dimensions of annealed article. Cooling should be uniform and slow to 500-400°C. Cooling of article is carried out together with furnace in ashes or sand. Here, carbon steels cool at rate of 100-200°C per hour, alloy steels at 20-60°C per hour, and further cooling can be performed in air.

In Fig. 8.14, as example, is given graph of annealing to granular perlite of Y8 carbon tool steel. From graph one may see that steel is heated to 750°C for 3 hours, sustained at this temperature for 9-10 hours, and cooled first with furnace to 550°C for 5 hours and then in air. Total duration of annealing is about 20 hours.

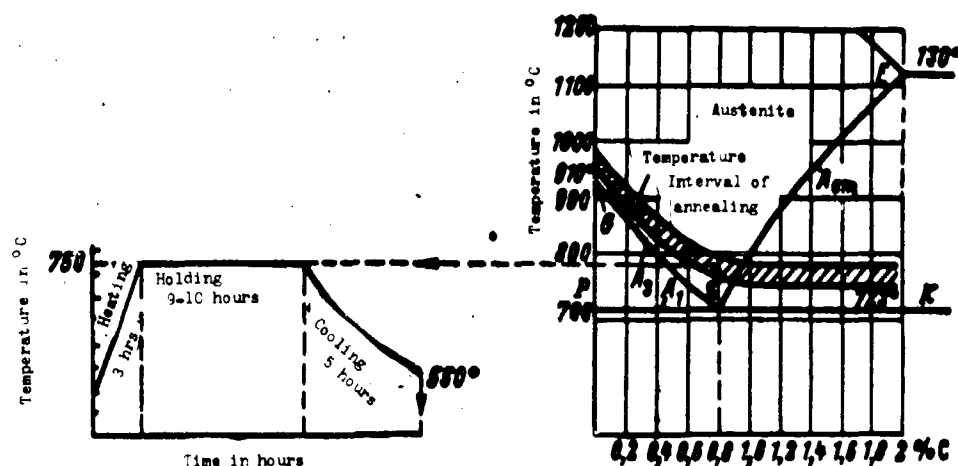


Fig. 8.14. Graph of annealing of carbon tool steels of grade Y8.

§ 3. Final Heat Treatment of Steel

Finished articles, depending upon conditions of work, must possess defined properties. Thus, parts working under conditions of prolongedly applied static loads must have high strength and sufficient toughness; tool should possess high cutting properties, ability to preserve these properties when heated during cutting, etc.

For guarantee of required properties finished articles are subjected to final heat treatment - hardening and tempering.

Hardening of Steel

Hardening is called heat treatment consisting of heating of steel to 30-50°C above line GSK, holding at this temperature, and subsequent fast cooling. During

hardening are posed different problems, depending upon assignment of steel: structural steels are imparted high strength, tool steels are given greatest hardness, ensuring high cutting properties and wear resistance.

Such changes of properties of steel during hardening are result of formation in it of unbalanced structures - martensite, troostite, sorbite. Practice of carrying out hardening of steel is based on phase transitions during heating and cooling. Through fast cooling of steel during hardening is prevented transformation of austenite to perlite and obtaining of one of intermediate structures of disintegration of austenite - martensite, troostite, or sorbite. By changing coolants during hardening there is selected rate of cooling necessary for production of required structure and properties.

In order not to cause stresses, hardening medium should cool fast in interval of temperatures of low stability of austenite (600-550°C) and slowly in interval of martensite transformation (300-200°C).

As cooling media for hardening the most widely applied are water and different mineral oils. For increase of cooling ability of water to it are added table salt, caustic soda, soda, sulfuric acid, etc. For lowering hardening ability of water to it is added scap, emulsion of oil, or it is heated.

For moderate cooling the best coolers are considered mineral oils, although they are inclined to self-ignition.

During isothermal hardening as hardening media are applied mixtures of nitrates ($\text{KNO}_3 - \text{NaNO}_3$ in 1:1 relationship) or oil with high flash point.

Basic technological property during hardening is hardenability. Hardenability of steel (depth of hardening) is depth of penetration of martensite or semi-martensite zone from surface inside article.

Surface layers of steel, touching hardening medium, are cooled faster than internal layers; therefore in article it not always is possible to obtain through hardenability. With incomplete hardenability structure, and this means properties of surface layers, will be different from structure and properties of internal layers. Hardness of surface layers, having structure of martensite, will be higher than hardness of internal layers, taking on structure of troostite or even sorbite. Depth of hardening depends mainly on composition of steel, temperature of heating before hardening, kind of coolant, and grain size. The stabler the austenite, i.e., the further to the right lies C-curve of isothermal disintegration of austenite, the

less the critical rate of hardening and the greater the hardenability of steel.

Least hardenability belongs to carbon steels, which are heated through only with thickness of sections up to 8-10 mm. Consequently, for big steel articles after hardening is observed heterogeneity of structure, and this means of properties throughout cross section. Alloy steels have greater hardenability than carbon steels. Certain grades of alloy steels are completely hardenable in sections of more than 100 mm. Therefore if it is necessary to obtain high strength and hardness over entire cross section, part is prepared from alloy steels. In practice hardenability is evaluated from hardness.

Methods of hardening. In practice is applied a series of methods of hardening, depending upon composition of steel, form of article, and hardness which it is necessary to obtain.

Depending upon temperature of heating, we distinguish full and incomplete hardening.

Full hardening is obtained during heating of steel above line GSE. It ensures, after cooling at critical rate of hardening, martensite structure for all carbon steels.

Incomplete hardening is obtained during heating of steel below line GSE but higher than PSK. As a result of cooling at critical rate of hardening, in hypoeutectoid steels is obtained ferrite and martensite structure and in hypereutectoid martensite and secondary cementite are obtained.

It is necessary to apply full hardening for articles of hypoeutectoid steels. Here, obtaining of soft ferrite inclusions will be eliminated. Incomplete hardening is profitably applied for tools of hypereutectoid steel, since presence of inclusions of secondary cementite increases hardness of hardened tool (cementite exceeds

martensite in hardness Fig. 8.15).

Depending upon conditions of cooling, we distinguish hardening in one coolant, intermittent hardening, step hardening, and isothermal hardening.

Hardening in one coolant (Fig. 8.16, curve 1) is accomplished by means of submersion of part in coolant, where it remains to full cooling. As coolant there most frequently is

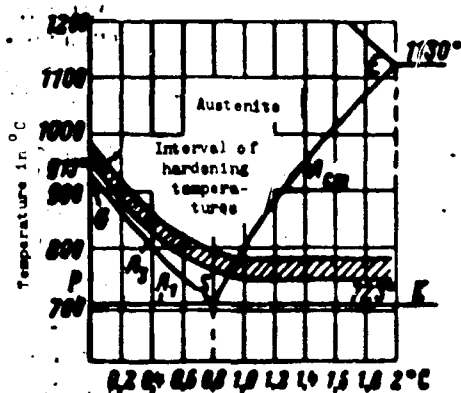


Fig. 8.15. Optimum interval of hardening temperatures of carbon steel.

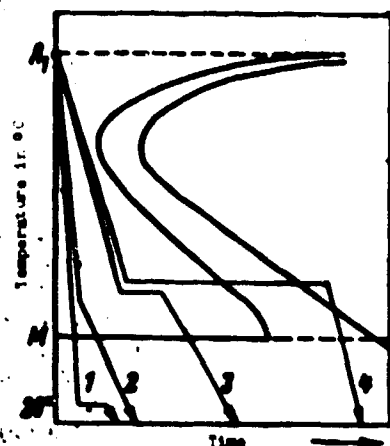


Fig. 8.16. Curves of cooling for different methods of hardening, plotted on diagram of isothermal disintegration of austenite. 1 - hardening in one coolant; 2 - intermittent hardening (hardening in two media); 3 - step hardening; 4 - isothermal hardening.

applied water (for carbon steel) and mineral oils (for alloy steel). So that no vapor layer is formed (steam jacket), which decreases rate of cooling, it is necessary to create energetic movement of parts in hardening medium. Hardening in one coolant is the simplest and most wide-spread method but can lead to considerable internal stresses.

For decrease of internal stresses there is applied hardening with partial cooling, for which part is held in air for a certain time before submersion in coolant. Here temperature of part must not drop below temperature of line GSK.

Intermittent hardening or hardening in two

media (see Fig. 8.16, curve 2) is executed by consecutive cooling of part, first in water to 300-350°C and then in oil or in air for more delayed cooling in interval of martensite transformation. This decreases internal stresses connected with transformation of austenite to martensite. Deficiency of given method of hardening is difficulty of control of time of holding in first coolant.

Step hardening (Fig. 8.16, curve 3) is produced by fast submersion of heated part in salt bath having temperature somewhat higher than martensite point; after small holding for temperature balance over entire section, article is cooled to room temperature in air. Advantages of step hardening are smaller internal stresses and decrease of warping. We apply this method only for hardening of small articles of carbon steels, since for big articles rate of cooling can be lower than critical in zone of low stability of austenite (600-500°C).

Isothermal hardening (Fig. 8.16, curve 4) differs from step hardening by more prolonged holding at temperature of quenching bath (above martensite transformation) for guarantee of full disintegration of austenite. Essence of isothermal hardening consists in that steel is heated to state of austenite and then sharply overheated to temperatures of isothermal disintegration of 250-300°C, corresponding to obtaining of acicular troostite. This structure is close in hardness to martensite but is tougher. Duration of holding in tempering medium is determined from diagram

of isothermal disintegration of austenite for given steel. Subsequent cooling is produced in air.

Isothermal hardening in this interval of temperatures gives steels high hardness (HRC = 45-55) and raised ductility as compared to usual hardening.

Basic advantage of isothermal hardening consists in that it does not cause in articles large internal stresses that frequently are the cause of warping and cracks of parts. But in order to avoid disintegration of austenite during isothermal hardening in the beginning is required high rate of cooling, not less than critical.

Therefore parts with diameter to 8-10 mm of carbon steels are subjected to isothermal hardening, since reserve of heat in more massive parts does not permit obtaining necessary rate of cooling. Majority of grades of alloy steel has lower critical rate of hardening and is well suited to isothermal hardening.

Decisive influence on quality of hardening is rendered by cooling. Cooling should be fast and full. This is attained by submersion of entire article in coolant, with obligatory mixing for constant contact of part with cold medium.

Quality of hardening is influenced also by method of submersion of parts in coolant. Small articles may be submersed in any position. Parts with large ratio of length to diameter or width should be submersed in coolant vertically.

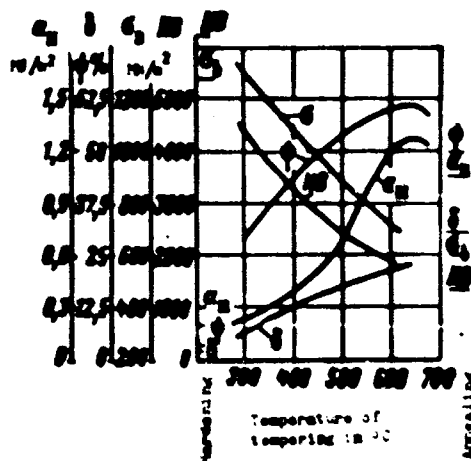
Tempering of Steel

Tempering is heat treatment consisting of heating hardened steels to temperature below line PSK (point A_{c1}), holding at this temperature, and subsequent arbitrary cooling.

Assignment of tempering consists in lowering internal stresses, decreasing hardness and brittleness, and increasing toughness and ductility of hardened steels to needed values, depending upon conditions of work of article.

As it was shown, after hardening are obtained different structures giving to article some or other properties. However, selection and supporting of necessary rate of cooling for articles of different dimensions and forms are conjugate with considerable difficulties. Therefore in practice for production of necessary structure of steel (and this means properties also) hardening and tempering are applied. At first article is hardened to martensite. Then hardened steel is tempered at 180-650°C. Here, martensite of hardening passes to stabler structures - troostite or sorbite (see Fig. 8.10).

During tempering of hardened steel there occurs also change of its properties. In Fig. 8.17 is shown influence of temperature of tempering on mechanical properties of hardened steel. From curves one may see that with increase of temperature of tempering, hardness (HB) and ultimate strength of steel (σ_B) drop and toughness (a_K) and indices of ductility (δ and ψ) are increased. Especially strong change of mechanical properties of steel takes place at temperatures of tempering higher than 400°C.



and majority of alloy steels after being tempered at 500-600°C be cooled in air.

For separate alloy steels for which there is observed lowering of impact toughness after tempering at temperatures of 450-600°C (temper brittleness) cooling in water or in oil is applied.

Depending upon temperature of heating of hardened steels, we distinguish following forms of temper: low, medium, and high.

Low temper is characterized by low temperatures of heating, to 250°C, at which martensite of tempering is formed. Low temper leads to insignificant decrease of hardness, increase of toughness, and also to decrease of internal stresses in parts. Such tempering is applied for tools and articles which have to possess high hardness and wear-resistance.

Medium temper is characterized by heating of hardened steels to temperatures of 350-500°C, at which structure of troostite of tempering is formed. Such tempering ensures obtaining in steel of sufficiently high hardness along with high elasticity. Medium temper is applied mainly for springs, dies, percussion tools, etc.

High temper is characterized by heating of hardened steel to temperatures of 550-650°C, at which internal stresses are removed completely and structure of sorbite of tempering is formed. As a result of high temper, steel obtains best complex of mechanical properties - raised values of strength, toughness, and ductility. Therefore double heat treatment, consisting in hardening to martensite and subsequent high tempering, is called by improvement of steel. High temper is applied for majority of parts of structural steels subject to action of high stresses.

Thus, tempering is necessary technological operation after hardening, ensuring the obtaining of required mechanical properties of steel.

To prevent cracking of articles after hardening due to large internal stresses, it is recommended that tempering be done as soon as possible after hardening.

Monitoring of temperatures during low tempering in the absence of pyrometer may be done in accordance with colors of iridescence appearing on surface of article polished with emery. Appearance of these colors is connected with appearance of fine films of oxides of iron on surface of part during its heating. Depending upon thickness of film, there appears defined color of iridescence - from light-yellow to gray (Table 4).

Table 4. Temperature of Colors of Iridescence

Color	Temperature °C	Color	Temperature °C
Light-yellow	220	Violet	285
Straw-yellow	240	Cornflower-blue	295
Brownish-yellow	258	Light-blue	315
Brownish-red	265	Gray	330
Purplish-red	275		and above

During determination of temperature from colors of iridescence one should consider that color of iridescence gives correct idea only of temperature of surface of article.

Aging of Steel

If low-carbon steel is cooled rapidly from temperatures of 600-700°C, then during subsequent holding occurs its aging, leading to increase of hardness and considerable lowering of ductility and toughness. Cause of aging is variable solubility of carbon in α -iron. During fast cooling from 700°C occurs fixation of supersaturated solid solution. During subsequent holding occurs disintegration of solid solution with precipitation of ultimate particles of tertiary cementite along line PQ of iron-carbon diagram which also involves change of properties of steel.

Process of aging is influenced more by temperature. Aging occurs naturally and artificially.

Natural aging occurs at room temperature. Maximum hardness during natural aging appears only after very prolonged holding.

Artificial aging occurs during heating of steel to temperatures of 100-170°C. Heating strongly accelerates process of aging. Artificial aging is used for stabilization of structures of properties and dimensions of measuring tool.

Besides this, for low-carbon steels aging is encountered after cold pressure treatment, called deformation aging. As a result of such aging, stampability of steel is worsened. Inclination of steel to aging is lowered through deoxidation of steel.

Conditions of Final Heat Treatment

Selection of conditions of final heat treatment depends on assignment of article (conditions of its work) and on chemical composition of steel. Thus for

tool which should possess high hardness and wear-resistance hardening is done in sharp coolants and low temper is applied (in case of its manufacture from carbon steel) or hardening in moderate coolants and low temper (in case of its manufacture from alloy steel). For different parts of structural steels, which have to possess good combination of strength and toughness sharp hardening and high temper are applied (in case of manufacture of them from carbon steel) or moderate hardening and high temper (for parts of alloy steels).

Results of final heat treatment are influenced by: temperature of heating, rate of heating, duration of holding at assigned temperature, and rate of cooling.

Temperature of heating. For hardening temperature of heating is selected from iron-carbon constitutional diagram. For tempering temperature of heating is determined by conditions of carrying out of some or other form of tempering.

Rate of heating during hardening has the same value and influence on metal as during annealing. Heating of articles of structural carbon steel (carbon 0.3-0.5%) should be done at such rate that necessary temperature is attained in one hour per every 25 mm of thickness. During tempering rate of heating does not play role.

Holding at the highest temperature of heating during hardening and tempering is determined by time necessary for full completion of structural transformations through entire thickness of article. Holding during hardening composes approximately 20-25% of time expended on heating and during tempering approximately one hour for every 25 mm of thickness of article. During tempering of articles of alloy steels time of holding is increased by one and a half or even twice as compared to shown norms for carbon steel.

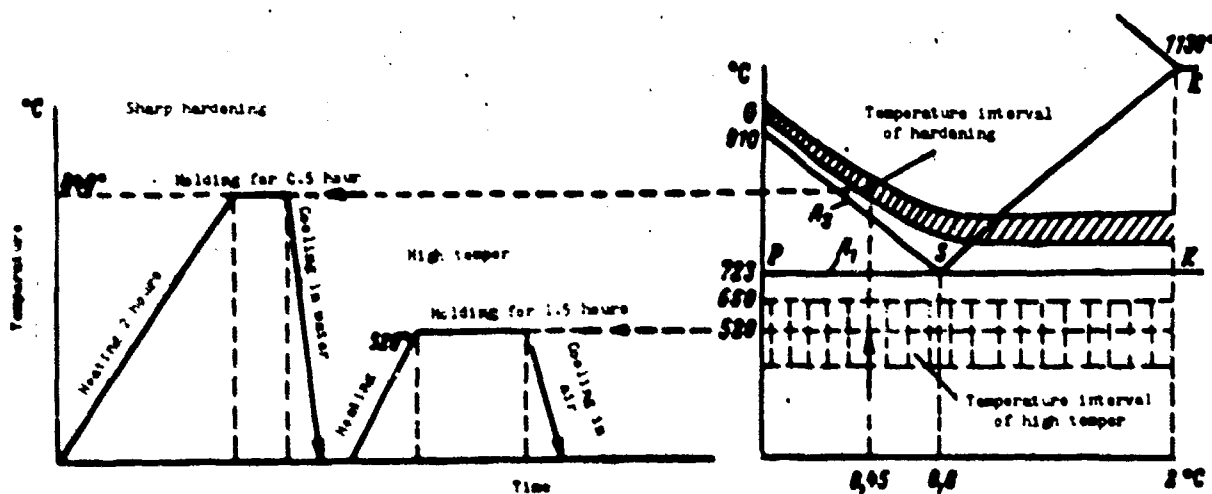


Fig. 8.19. Graph of hardening and tempering of structural carbon steel (steel 45) containing 0.45% C.

Rate of cooling during hardening should ensure formation of needed structure from austenite: martensite, troostite, or sorbite. During tempering rate of cooling in most cases does not have value. But still it is preferred that articles cool slowly, since during fast cooling internal stresses appear. Alloy steels inclined to temper brittleness are an exception; they are cooled after heating not in air but in water or oil.

As example, in Fig. 8.19 is presented graph of hardening and tempering of a shaft of steel 45 (containing 0.45% carbon).

§ 4. Defects of Heat Treatment of Steel

All defects which can appear during heat treatment are consequence of disturbance of conditions of technological process.

Defects of Annealing and Normalization

During annealing and normalization there frequently are encountered the following defects: overheating, burning, and decarburization.

Overheating of steel. Very high temperature of heating during annealing leads to large growth of grains of austenite and formation of coarse-grained structure (Fig. 8.20). Such steel is brittle and of lowered strength. Phenomenon of formation of coarse-grained structure as result of high-temperature heating of steel is called overheating, which can be removed by means of secondary full annealing.

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Fig. 8.20. Structure of overheated steels, $\times 400$.



Fig. 8.21. Structure of burnt steel, $\times 300$.

Burning of steel is characterized by strong growth of grains and appearance of oxides on grain boundaries (Fig. 8.21). Burning is result of prolonged holding at considerably raised temperature as compared to that permissible for given grade of steel. This defect imparts raised brittleness to steel. Burning is incorrigible defect, and burnt part goes to scrap.

Decarburization. As a result of chemical interaction at high temperature between steel and atmospheric oxygen in furnace, its decarburization and oxidation occurs.



Fig. 8.22. Structure of decarburized surface of steel. a) decarburized layer, $\times 100$.

Decarburization of steel is connected with burning out of carbon in surface layers (Fig. 8.22). Such steel possesses lowered hardness. Besides, as a result of oxidation of steel, on surface of part there forms cinder consisting of oxides of iron. To prevent decarburization and oxidation of steel during its heating, at present furnaces with protective (controlled) atmosphere are applied, i.e., filling with inert gases.

Considered defects can take place not only during annealing or normalization but also during other operations of heat treatment.

Defects of Hardening and Tempering

As result of change of volume during heating and nonuniform cooling of internal and external layers during hardening, the following defects are possible: hardening cracks, warping, insufficient hardness, raised brittleness, formation of soft spots, and others.

Hardening cracks are the most dangerous and incorrigible defect. Formation of cracks is result of appearance in part of stresses whose magnitude exceeds ultimate strength of steel. Internal stresses appear in connection with change of volume of steel during heating and cooling and also during transformation of austenite to martensite. Sharp corners, cuts, and scratches left by tool on article lead to appearance of cracks in these places during hardening.

In order to prevent appearance of cracks one should evenly heat such parts without overheating them and cool them in soft hardening media (oil).

Warping is consequence of internal stresses appearing in steel as a result of nonuniform heating or nonuniform cooling.

Warping depends on form of part, difference in wall thickness, presence of sharp transitions, and can appear on parts of complicated configuration. Warping can also appear in the form of shrinkage or swelling.

To prevent warping, one should make heating and cooling as uniform as possible. It is recommended that complicated parts be hardened in dies, special clamps, or hardening attachments.

Warping can lead to full spoilage, but in certain cases it can be removed by mechanical correction of parts.

Insufficient hardness of hardened part can be obtained for the following causes: temperature of heating before hardening less than required for given grade of steel; too little holding at working temperature of heating; insufficient rate of cooling; strong decarburization from surface. It is possible to correct this defect by repeated hardening with exact observance of conditions of heat treatment. Low hardness after tempering occurs as a result of excessive temperature of tempering or of prolonged holding at normal temperature of tempering. It is possible to correct this defect only by correctly conducted hardening and tempering.

Here, before repeated hardening there first have to be removed internal tempering stresses by annealing, normalization, or high tempering.

Raised brittleness is consequence of excessive temperature of heating before hardening and also of incorrectly conducted tempering. It is possible to correct this defect also by correctly conducted hardening and tempering.

Formation of soft spots. During hardening of steel articles, in different places on surface of hardened article sometimes is observed unequal hardness. Soft spots can be due mainly to insufficient heating of articles or their insufficiently fast cooling. Sometimes soft spots are due to nonuniform initial structure of steel and formation of so-called steam jacket during submersion of part in tempering medium.

§ 5. Special Methods of Heat Treatment of Steel

Sub-Zero Treatment of Steel (Hypothermia)

Sub-zero treatment, i.e., at negative temperatures, is applied to steels for which after hardening considerable quantity of residual austenite is kept. As it was shown earlier, martensite transformation (M_s) for steels containing more than

0.6% carbon is finished below room temperature (see Fig. 8.17). During usual hardening austenite-martensite transformation consequently is not complete and in steel certain quantity of austenite is maintained. With increase in steel of carbon content or alloy elements, quantity of residual austenite strongly increases. Sub-zero treatment of these steels causes transformation of residual austenite of hardened steels to martensite. Here, hardness and strength are increased and magnetic properties are improved.

Sub-zero treatment consists in cooling hardened part below zero (from -40 to -190°C). Temperature of sub-zero treatment is selected depending upon composition of steel from which part is prepared. To prevent stabilization of austenite, lowering effect of sub-zero treatment, cooling must be produced directly after hardening or after small interval of time.

Sub-zero treatment is used for:

- increase of wear-resistance and cutting ability of tools made from high-speed cutting and other tool steels;

- stabilization of dimensions of measuring tools and parts working at low temperatures;

- increase of hardness and wear-resistance of many parts prepared from high-carbon and stainless steels.

For parts of complicated form before sub-zero treatment usual tempering is applied. Its purpose is to remove tempering stresses and thereby prevent appearance of cracks and warping.

Low temperatures for sub-zero treatment are obtained by applying liquid oxygen, nitrogen, or air, a mixture of dry ice with acetone, and others.

Surface Hardening of Steel

Essence of surface hardening consists in that heat treatment is applied only to surface layer, to a small depth. Here, the core remains ductile and surface layer obtains high hardness. Surface hardening is done for the same purpose as carburizing, nitriding, and cyanidation, but it has a series of advantages as compared to other methods of surface hardening.

Heating of surface layer of part can be carried out with help of currents of high frequency, by gas flame, and in electrolyte.

Surface hardening by currents of high frequency was proposed and developed by

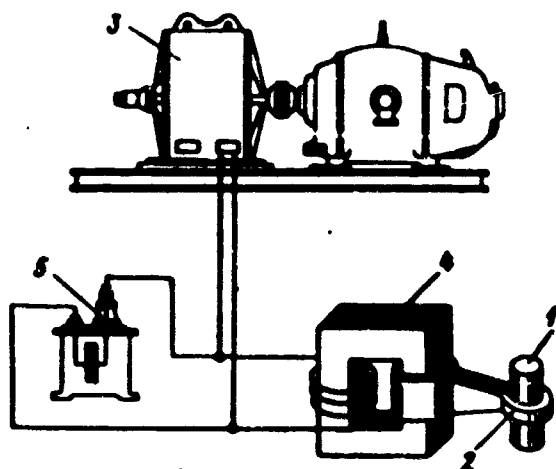


Fig. 8.23. Diagram of installation for high-frequency hardening. 1 - hardened part; 2 - inductor; 3 - high-frequency oscillator; 4 - hardening transformer; 5 - battery of capacitors.

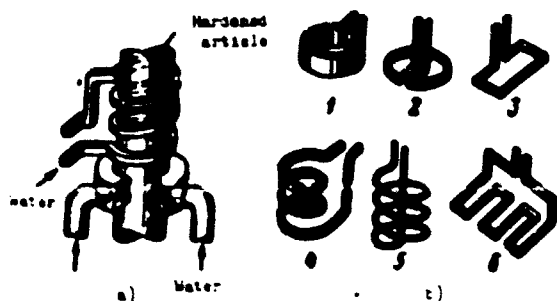


Fig. 8.24. Inductors for high-frequency hardening. a) inductor with cooler; b) types of applied inductors. 1, 4 - for external cylindrical surfaces; 2, 5 - for internal cylindrical surfaces; 3 - for brackets of complicated form and plates by method of shift; 6 - for plates and planes by method of shift.

Prof. V. I. Volynin. Essence of method of surface hardening by currents of high frequency [hf] (T.B.U.) consists in that part is placed, with considerable air gap, inside special inductor. Inductor is copper tube (oval or square), bent in form of heated part, in which water circulates for the purpose of cooling. Then through inductor is passed an electrical current of high frequency (from 500 Hz to 10 MHz) and great force. Resultant electromagnetic high-frequency field excites eddy currents, which heat surface of part. Depth of heated layer depends on frequency of current and duration of heating. The higher the frequency of current the less its penetration into part. The greater the duration of heating the bigger the depth of layer.

By regulating frequency of current and time of heating it is possible to attain required depth of heating and, consequently, depth of hardened layer.

During treatment of different articles it varies from 1 to 10 mm.

In Fig. 8.23 is presented diagram of installation for hardening through heating by hf.

Cooling of surface layer is done either through inductor, which in this case is made hollow and has holes directed towards part, or a dryer is placed in series with inductor (Fig. 8.24a).

In Fig. 8.24b are shown types of inductors for surfaces of hardening of series of parts.

As compared to usual hardening, high-frequency hardening has following

advantage. Process of treatment of articles is accelerated tens of times and is more productive; heating is not accompanied by oxidation and decarburization, warping is eliminated, and cracks are absent. Therefore hardening by high-frequency currents is the most progressive method of heat treatment and is being ever more adopted in practice of machine building.

Surface hardening with heating by gas flame consists in the following:

oxyacetylene flame of gas burner, having temperature near 3100°C , is directed on surface of processed part and heats it to hardening temperature. Cooling is produced by water from tube following burner (Fig. 8.25). By this method can be obtained hardened layer of depth to 6 mm.

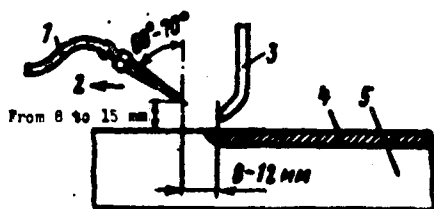


Fig. 8.25. Diagram of oxyacetylene surface hardening. 1 - burner; 2 - direction of movement of burner; 3 - tube for cooling water; 4 - hardened surface of article; 5 - nonhardened part of article.

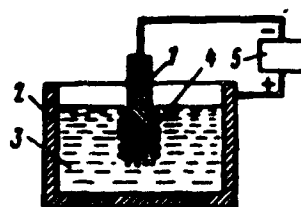


Fig. 8.26. Diagram of electrical heating of part in electrolyte. 1 - heated part (cathode); 2 - bath (anode); 3 - electrolyte; 4 - hydrogen shell; 5 - source of current.

By applying oxyacetylene flame it is impossible to obtain uniform heating of steel from surface. Besides, with this method of heating is obtained structural heterogeneity of hardened layer. Therefore oxyacetylene heating is applied comparatively rarely.

Surface hardening with heating in electrolyte is produced with help of electrical current of high voltage (330-380 V), passed through electrolyte in which heated articles are placed (Fig. 8.26). On surface of article forms shell of hydrogen. This shell creates high resistance to passage of current, in consequence of which surface heating of article occurs. After achievement of assigned temperature, current is turned off and article is cooled in the same electrolyte.

After being hardened, parts are subjected to low temper at a temperature of $160-220^{\circ}\text{C}$ for 1.5-2 hours for removal of internal stresses.

Advantage of this method is that parts hardened in electrolyte show practically no oxidation and are not deformed.

CHAPTER IX

CHEMICAL-HEAT TREATMENT OF STEEL

Chemical-heat treatment is process of saturation of surface of steel article by chemical elements - carbon, nitrogen, aluminum, silicon, chromium, and others.

Assignment of chemical - heat treatment is to increase surface hardness with preservation of ductile core, to increase wear resistance at normal and raised temperatures, to increase fatigue strength and corrosion resistance. Chemical-heat treatment is based on use of process of diffusion, which can be carried out only in that case when diffusing element is dissolved in the basic metal of article. Here, the following processes take place:

- 1) dissociation, i.e., decomposition of molecules of diffusing element with formation of atoms;
- 2) adsorption, i.e., absorption of atoms by surface of steel;
- 3) diffusion, i.e., penetration of atoms into surface layers of steel articles.

For carrying out chemical-heat treatment articles are placed in medium rich in saturating element (C, N, Al, Cr, Si, and others), and they are heated to defined temperature.

With increase of temperature of process, concentration of saturating element in hardening layer is increased. Duration of process depends on required depth of layer.

Chemical-heat treatment is applied widely in those cases when parts work under wear and are subject to impact loads and when with high surface hardness ductile core is needed. Such parts include various kinds of gears, pins, bushings, sleeves, shafts, and others.

In airplane industry are applied following heat treatment of steel: carburizing, nitriding, cyanidation, and diffusion nitriding.

9.1. Carburizing of Steel

Carburizing is process of saturation of surface layer of steel by carbon. Process of carburizing is based on ability of carbon to dissolve in γ -iron.

Assignment of carburizing is to change properties of article by changing its chemical composition and structure of surface layer. By applying heat treatment after carburizing we obtain high surface hardness with preservation of soft and ductile core, which increases wear resistance and fatigue limit of steel parts.

Carburizing is the most wide-spread operation of chemical-heat treatment. Examples of parts subjected to carburizing are gears, pins, camshafts, shafts, levers, worms, and others, and also bearings parts. Carburizing is applied to carbon and alloy steel with low carbon content (0.1-0.2%), which is due to necessity of obtaining ductile core in article. Recently for many parts carbon content in steel has been increased to 0.3% for the purpose of increasing strength properties of core. Parts are carburized after final machining, with small allowance for final grinding. Portions of part not subjected to carburizing are protected by special masking, copper film applied by electrolytic method, or by leaving an allowance to be removed by machining. For carburizing articles are placed in medium rich in carbon, called carburizer.

Results of carburizing depend on following factors:

- 1) conditions of carburizing (temperature and time of holding);
- 2) composition of carburizer;
- 3) composition of steel;
- 4) conditions of heat treatment after carburizing.

According to kind of applied medium, we distinguish carburizing in solid, gas, and liquid carburizer (the last one is applied rarely).

Carburizing in solid carburizer. Cleaned parts are loaded into metallic box filled with carburizer and are heated in carburizing furnace (Fig. 9.1). Carburizer is pulverized charcoal with addition of different carbonate salts, accelerating process of carburizing (soda, potash, and others). Most widely used are carburizers of the following composition: barium carbonate 20-25%, soda 3-5%, coke 5%, the remainder charcoal. Temperatures of heating of steel are selected from iron-carbon

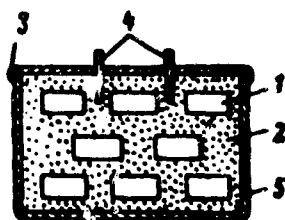
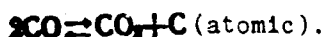


Fig. 9.1. Packing of parts in box for carburizing by solid carburizer. 1 - parts, 2 - carburizer, 3 - putty, 4 - samples, 5 - carburizing box.

constitutional diagram above point Ac_3 by 30-50°. Usually it is equal to 900-950°. At this temperature carbon of carburizer, combining with oxygen of atmosphere, forms carbon monoxide CO per reaction



Carbon monoxide upon contacting parts is decomposed to carbon dioxide CO_2 and atomic carbon:



Formed active carbon diffuses in metal, forming solid solution with γ -iron. Carbonate salts in carburizer accelerate process, promoting additional formation of active atomic carbon. Process of diffusion occurs during prolonged holding,

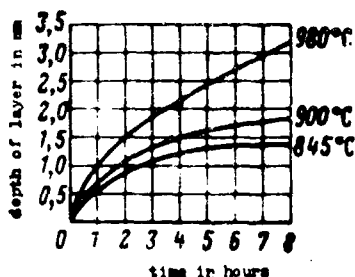


Fig. 9.2. Influence of temperature and time of holding on depth of carburizing by solid carburizer (charcoal + 40% $BaCO_3$).

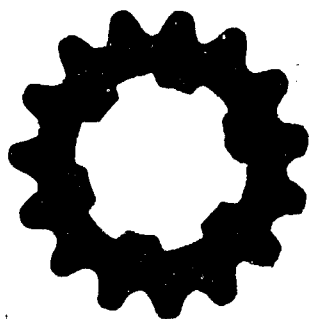
established in dependence upon necessary concentration of carbon and thickness of carburized layer (Fig. 9.2).

Usually for production of carburized layer with depth of from 0.5 to 2 mm holding is from 5 to 12 hours. Termination of process of carburizing is judged from depth of carburized layer. Carburized layer is determined with help test samples, which are inserted in carburizing box in such a manner that their ends extend above cover. In process of carburizing these samples are removed, and depth of carburizing is judged from their fracture.

More exact determination of depth of carburized layer is made through metallographic analysis. The latter is widely applied also for judgement of uniformity of distribution of carburized layer over contour of part (Fig. 9.3).

After carburization box together with parts is removed from furnace and cooled in air.

Fig. 9.3. Macrostructure of gear with carburized teeth.



Essential deficiencies of process of carburizing in solid carburizer are abundance of dust and dirt, difficulty of control, labor involved, and low productivity.

Gas carburizing consists in saturation of surface layer of steel articles by carbon during heating of them in atmosphere of carbon-containing gases. In composition of carburizing gas enter carbon monoxide and gaseous hydrocarbons: methane, ethane, propane, and others. For gas carburizing are applied natural and artificial gases, obtained during decomposition of oil products. Besides these, there are used liquid carburizers (kerosene, synthine).

At present gas carburizing finds wide application in mass and heavy-serial production.

For gas carburizing parts are placed in special chambers, muffles, through which pass carburizing gas. In chambers is maintained temperature of 900-930°C. At this temperature gases flowing around part are decomposed, with formation of atomic carbon.

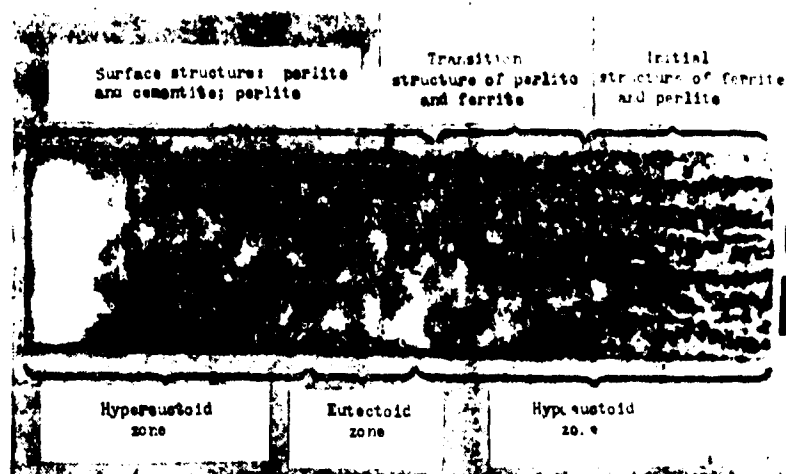
Duration of carburizing process depends on required depth of carburized layer. Thus, for production of depth of carburizing of 0.5-1.5 mm time required is 2-3 hours.

As compared to carburizing in solid carburizer, gas carburizing has following advantages:

- 1) higher productivity of process;
- 2) assigned depth of carburized layer and desirable distribution of carbon in it are attained considerably more simply, thanks to possibility of control through progress of process of temperature and composition of gas;
- 3) there is the possibility of full mechanization and automation of process;
- 4) necessary workshop area is halved;
- 5) briefer holding of parts in process of carburizing decreases possibility of overheating of parts, which permits producing hardening (with partial cooling) directly from carburizing furnaces.

During gas carburizing intensification of process is possible through increase of working temperature (heating by high-frequency currents).

Microstructure of carburized layer. Structure of carburized steels is nonuniform in cross section, since different sections contain different quantity of carbon. For normally conducted process of carburizing in surface layers of steel is contained 1.0-1.2% carbon (with greater content brittleness of layer is observed). With distance from surface of part toward core carbon content decreases to initial (0.1-0.2%).



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Fig. 9.4. Microstructure of carburized steel.

Structure of carburized layer after slow cooling from temperature of carburizing is shown in Fig. 9.4. It consists of three zones: first zone contains 1.2-0.9% carbon, consists of perlite and cementite, and is called hypereutectoid zone; second zone contains 0.8% carbon, consists of perlite above, and is called eutectoid; third zone, with content of 0.7-0.1% carbon, consists of ferrite and perlite and is called hypoeutectoid (transition) zone. This zone connects carburized layer with basic metal. The nearer to the core the less perlite and the more ferrite in transition zone.

As technical depth of carburized layer usually is taken distance (in mm) from surface to half of transition zone. Depth of carburizing of aviation parts varies from 0.5 to 3-4 mm.

Heat treatment of carburized parts. Through carburizing is achieved only suitable distribution of carbon over cross sections of part. After carburizing part must be subjected to heat treatment, which has the following purpose: to remove coarse-grainedness of steel, formed as a result of prolonged holding at high temperature; to give part high hardness and wear-resistance of surface, with ductile core.

Most frequently after carburizing is applied following heat treatment:

1. Normalization or hardening in oil from temperature of 860-880°C. Purpose of this operation is to destroy cementite network and to remove overheating (to crush structure) of core of part.
2. Hardening in water or oil from temperature of 760-800°C for removal of overheating of carburized layer caused by first hardening from high temperature (860°C) and imparting high hardness to layer. Parts of simple configuration made

from steels with carbon content of 0.1-0.2% usually are cooled in water; those of complicated configuration are cooled in oil; parts of special steels are cooled in oil.

3. Tempering at a temperature of 150-170°C for 2-4 hours for removal of internal stresses.

The simplest form of heat treatment after carburizing is direct hardening from carburizing furnace with preliminary partial cooling to 820-840°C and tempering at 180-200°C.

Such hardening is applicable only after gas carburizing for parts prepared from natural fine-grained steels. Only in this case will fine-grained structure be preserved, warping be lowered, and content of residual austenite on surface be reduced.

For destruction of residual austenite in carburized and then hardened parts, sub-zero treatment is applied.

After heat in surface layer is formed martensite structure and carbides with hardness HRC = 60-64.

After carburizing the following flaws are encountered: coarse-grained structure, soft places on surface, and formation of soot on parts with gas carburizing. Increase of grain size of steel is result of high temperatures of heating and prolonged holdings. It is necessary to apply steels with small natural grains or to apply heat treatment for removal of coarse-grained structure.

Soft places on surface of parts after hardening can be the result of insufficient carburization, heterogeneity of concentration of carbon in initial austenite, or insufficiently fast cooling during hardening.

To prevent formation of soot on parts, preventing penetration of atomic carbon to surface of part, it is necessary to select composition of carburizing gas correctly and to designate conditions of gas carburizing.

§ 2. Nitriding of Steel

Nitriding is process of saturation of steel articles by nitrogen. Through nitriding are increased hardness, wear-resistance, and strength of surface layer of article, and corrosion resistance of steel is increased in such media as atmosphere, superheated steam, fresh water, etc.

To nitriding, as a rule, are subjected machine parts subject to wear at high

temperatures and parts working in atmosphere of exhaust gases. Such parts include cylinder sleeves, valves, gears, shafts, and so forth.

Process of nitriding was first proposed by Academician N. P. Chizhevskiy. Wide introduction of process of nitriding was due to works of N. A. Minkevich, Yu. M. Lakhtin, V. I. Prosvirin, and others.

Change of properties of steel through nitriding is result of formation in surface layer of nitrated articles of nitrides – stable chemical compounds of nitrogen with other elements (iron, aluminum, chromium, molybdenum, vanadium, and others).

Nitriding of carbon steels does not ensure sufficient surface hardness; therefore nitriding is applied to alloy steels containing elements forming stable nitrides.

Technique of nitriding consists in the following: since nitriding is one of finishing operations of technological process, parts subjected to nitriding after final machining are heat-treated to give them necessary properties and then are nitrated.

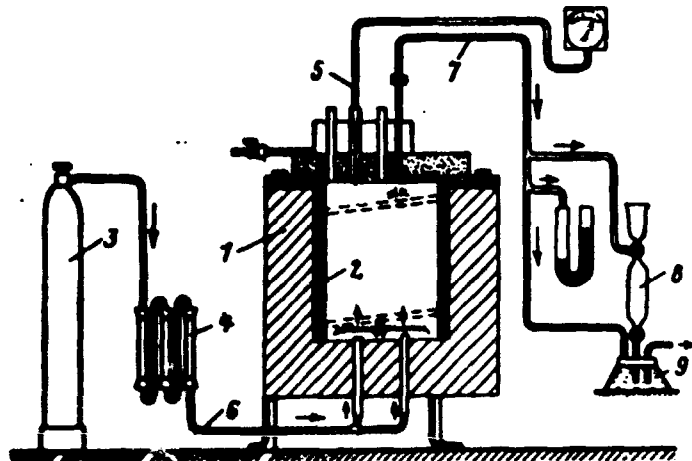
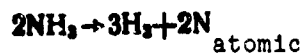


Fig. 9.5. Diagram of installation for nitriding
1 – furnace for nitriding, 2 – door, 3 – ammonia bottle, 4 – drier, 5 – pyrometer, 6 and 7 – tubes for feed and removal of ammonia, 8 – dissociation meter, 9 – tank for cooling gases.

When nitriding is not applied to entire surface of part, those portions not to be nitrated are covered with special masking or a thin layer of tin is deposited by electrolytic means. After this, parts are loaded in tightly closed muffle of furnace (Fig. 9.5), through which at defined speed is passed ammonia (NH_3).

Depending upon accepted conditions of nitriding, furnace is heated to assigned temperature, which is sustained for defined time. Ammonia entering hot furnace is decomposed, with precipitation of atomic nitrogen, which diffuses into surface layers of steel part and forms nitrides. Ammonia is decomposed in hot furnace per reaction:



Upon termination of process furnace with parts is cooled slowly. After nitriding part is subjected only to final grinding.

Basic factors affecting process of nitriding are: temperature and duration of nitriding and degree of dissociation of ammonia.

The higher the temperature of nitriding the lower the hardness of nitrided layer but the faster the diffusion of nitrogen into steel.

Degree of dissociation of ammonia is from 15 to 45%, depending upon temperature of nitriding.

To obtain hardness and wear-resistance, there are nitrided mainly steels containing aluminum, chromium, molybdenum, and vanadium. In aircraft construction most frequently nitrided are parts made from alloy chromium-molybdenum-aluminum steel [38KhMYuA] (38XMKOA) of composition 0.3-0.4% C; 1.35-1.65% Cr; 0.2-0.3% Mo; 0.7-1.2% Al. In this case the process of nitriding is conducted at a temperature of 500-520°C for 20-60 hours, depending upon required depth of layer. There usually is obtained layer with depth of 0.25-0.65 mm and nitrogen concentration of 3-4%. Higher nitrogen content causes raised brittleness in steel. Hardness after nitriding attains 1200 MN/m² Vickers.

For acceleration of process of nitriding a two-stage process is applied. In the beginning nitriding is conducted at a temperature of 500-520°C, which provides nitrided layer of required hardness. Then process is continued at 600-620°C, which decreases time required to obtain assigned depth of nitrided layer. This accelerates process by 1.5-2 times and has almost no effect on quality of nitrided layer.

For increase of fatigue strength alloy structural steels are nitrided. As a result of nitriding of these steels, in surface layer of article are formed compressive stresses, which increases their endurance. Hardness of surface after nitriding in this case attains 600-800 MN/m² Vickers.

For increase of corrosion resistance both alloy and carbon steels are nitrided. Process is conducted at high temperature (600-700°C) and is completed in less time (0.5-6 hours). Here, on surface is formed mainly iron nitride Fe_2N , being the most corrosion-resistant.

As compared to carburizing, nitriding has the following advantages:

- hardness of nitrided layer is 1.5-2 times higher than hardness of carburized layer, which considerably increases wear-resistance of part;
- nitrided layer does not lose its hardness when heated to 500-600°C, whereas hardness of carburized layer is lowered at temperatures of 250°C;
- hardening of parts to be nitrided is done before nitriding and carburized parts are hardened later, which leads sometimes to spoilage of parts (warping);
- carburized surface is less resistant to corrosion than nitrided surface.

Deficiencies of nitriding are high costs and duration of process and also ineffectiveness of nitriding of carbon steels.

§ 3. Cyaniding of Steel

Cyaniding is process of simultaneous saturation of surface of steel by carbon and nitrogen. Purpose of cyaniding is to increase hardness and wear-resistance of surface layer of articles and also to increase their corrosion resistance. Cyaniding is less widely applied in aviation industry than carburizing and nitriding.

Liquid, gas, and solid cyaniding are applied. Most widely applied is cyaniding in liquid and gaseous media.

Liquid cyaniding is done in molten cyanide salts (sodium cyanide NaCN , potassium cyanide KCN , calcium cyanide $\text{Ca}(\text{CN})_2$, and others). For increase of fusion temperature and less evaporation of cyanide neutral salts are added to them (sodium chloride NaCl , barium chloride BaCl_2 , and others).

When cyanide salts are melted, they decompose, forming nitrogen and carbon, which diffuses into surface of article, nitriding and carburizing it.

Basic factors determining depth and concentration of cyanided layer are temperature of heating and time of holding. The higher the temperature the less nitrogen and the more carbon in layer. The longer the holding time the deeper the cyanided layer.

Before being cyanided, articles are completely processed mechanically and those portions not to be cyanided are covered by protective layer. Then articles are

loaded in bath with molten cyanide salts for defined time. After cyanidation parts are hardened and given low temper. Microstructure of cyanided layer after hardening consists of the following zones: nitrous martensite on surface and troostite in core.

We distinguish low-temperature cyaniding, applied for tools, and high-temperature cyaniding, applied for structural carbon and alloy steels.

Low-temperature cyanidation (550-600°C) is applied mainly for increase of cutting properties of tools made from high-speed cutting steels. Duration of process is 60-80 minutes, depth of layer is 0.03-0.05 mm. With this process nitriding is superior to carburizing.

High-temperature cyanidation (800-840°C) is used for obtaining of deeper diffusion layer, resistant to wear under small specific loads. Duration of process is from 5 to 90 minutes, depth of layer is 0.2-0.5 mm. With this process carburizing is superior to nitriding.

For production of deeper layers deep cyaniding is applied. Process is conducted at 900-950°C for 1-6 hours. With this process there forms a layer with depth of 0.5-2 mm, containing 1-1.2% carbon and 0.2-0.3% nitrogen.

Deep cyaniding fully replaces carburizing in results but takes place considerably faster.

After cyaniding there is obtained a quite hard layer (HRC = 63-65).

Deficiency of process is poisonous nature of cyanide salts, which necessitates that thorough precautions be taken.

Gas cyaniding (nitrogen case hardening) is produced in mixture consisting of 75% carburizing gas and 25% ammonia. Carburizing gas (pyrolysis and generator gases, Saratov gas, and others) is decomposed in furnace, with precipitation of atomic carbon, and ammonia, with precipitation of active nitrogen. Process is conducted at 800-840°C and holding of from 1 to 6 hours. After cyaniding is produced hardening of articles. Depth of cyaniding here is 0.4-0.6 mm, and hardness of hardened cyanided layer is not below 56 HRC.

Gas cyaniding, as compared to gas carburizing, has the following advantages: lower temperature of process; smaller duration of process; twice greater wear resistance of cyanided layer; smaller growth of grains in core, which makes it possible to harden parts directly from furnace.

§ 4. Diffusion Metallizing

Diffusion metallizing is process of saturation of surface of steel by metal. For this purpose is applied mainly aluminum (calorizing), and less often chromium (chromizing) and silicon (siliconizing).

Diffusion metallizing is produced by means of heating and holding of steel parts in contact with substances containing saturating element. Diffusion metallizing increases resistance to scaling, corrosion resistance, and also hardness and wear-resistance. High temperatures and duration of processes of diffusion metallizing limit their application. Practical value so far has been found for process of calorizing. Less widely applied are diffusion chromizing and siliconizing.

Calorizing is process of surface saturation of layer of steel with aluminum. Calorizing is applied during treatment of different parts of carbon steel for the purpose of increasing their resistance to scaling. Calorized parts do not oxidize and work stably at temperatures up to 800-900°C. Process of calorizing permits replacement of expensive high-alloy steels by cheaper carbon steels for parts subjected to multiple heating. Resistance to scaling of calorized steels is explained by the fact that during work under conditions of high temperature on surface of part there forms durable film of Al_2O_3 oxides. This film protects part from further oxidation.

Applied are solid, liquid, and gas calorizing.

Solid calorizing finds greatest application. Essence of process consists in heating of parts in boxes with calorizing mixture, whose composition includes powdered aluminum or ferroaluminum, ammonium chloride, and inert additions - aluminum oxide, kaolin, and chamotte. Temperature of calorizing is 950-1050°C, time of holding is 4-12 hours, depth of layer is from 0.1 to 2 mm.

Liquid calorizing is applied basically for small parts. Essence of it consists in that parts are submerged for 40-90 minutes at temperature of 750-800°C in molten aluminum saturated by iron (7-8%). Iron is included in order to prevent intense dissolution of steel part in liquid aluminum. Depth of layer is 0.2-0.3 mm. Deficiency of method is raised brittleness due to its supersaturation by aluminum.

Gas calorizing is produced at 1000°C in vapors of aluminum chloride $AlCl_3$. After 2 hours calorized layer of 0.2 mm depth is obtained.

Calorizing, increasing resistance of steel to scaling simultaneously imparts

to its poor wear resistance. To lower brittleness of calorized layer, diffusion annealing is applied to calorized parts at 900-1150°C for 5-6 hours.

Depth of calorized layer depends on temperature of heating, duration of process, composition of mixture, of state of surface of article, and carbon content in steel.

The higher the temperature and the greater the duration of calorizing the depth of layer. Presence of scale on surface of article delays process of diffusion of aluminum. To calorizing are best suited steels containing small quantity of carbon, since carbon retards diffusion rate of aluminum. Majority of alloy elements also delays process of calorizing, thereby lowering depth of layer.

Diffusion chromizing is process of saturation of surface layer of steel by chromium. Purpose of diffusion chromizing is to obtain high surface hardness and wear resistance and also to increase corrosion resistance at high temperatures (to 800°C).

Applied are solid, liquid, and gas chromizing. Most widely applied is solid diffusion chromizing. It is produced in mixture consisting of 60-65% ferrochrome, 30-35% alumina, and 5% hydrogen chloride (ammonium chloride). Process is conducted in furnaces at a temperature of 1050-1150°C for 12-15 hours. Before being loaded in furnace, parts are placed in iron boxes filled with the indicated mixture. Surface hardness of chromized low-carbon steel is low and approximately equal to 200-250 Vickers units. For high-carbon steel it attains 1380 units and exceeds hardness of not only carburized and hardened but also nitrided steels.

Siliconizing is process of saturation of surface layer of steel by silicon. Siliconized layer possesses high acid-resistance, is heat-resistant to 850°C, and wear resistance. Therefore it is expedient to apply siliconizing for parts working under abrasion in aggressive media. Siliconizing is conducted in gas, and less often in solid, media.

Gas siliconizing is produced at 950-1050°C in vapors of silicon chloride. After termination of process, parts are cooled in furnace to 500-400°C and then in air.

Process of gas siliconizing is very intense. Thus for production of layer of 1-mm depth duration of holding at 1050°C does not exceed 2 hours.

For diffusion metallizing saturation of steel by other metals is possible. Thus, there sometimes is applied saturation of surface of steel by beryllium (beryllizing). Beryllized layer is characterized by great hardness and high heat resistance.

S E C T I O N T W O

FERROUS METALS AND SPECIAL ALLOYS

CHAPTER X

CARBON STEELS

Carbon steels in aviation industry have limited application. This is explained by the fact that they possess a series of deficiencies. With increase of carbon content strength and hardness are increased, but simultaneously ductility and toughness are sharply reduced and brittleness is increased.

In connection with high critical rate of hardening, carbon steels possess low hardenability. As a result of hardening, only surface of part takes on structure of martensite; internal layers are hardened to troostite or sorbite and for massive parts are not hardened at all.

In addition to that, carbon steels do not satisfy certain special requirements imposed on a series of parts of motors, aircraft, and their equipment, such as heat resistance, resistance to scaling, acid resistance, special magnetic and thermal properties, and others.

§ 1. Influence of Carbon and Constant Impurities on Properties of Steel

In carbon steels, besides basic elements of iron and carbon, there constantly are present the following impurities: manganese and silicon (introduced as deoxidizing agents), sulfur and phosphorus (inevitably coming from ore and fuel).

Let us consider influence of carbon and constant impurities on properties of steel.

Influence of carbon. Carbon is basic element of carbon steels and strongly affects their mechanical and technological properties.

In Fig. 10.1 are given curves of change of mechanical properties of steel depending upon carbon content. Hardness (HB) and ultimate strength (σ_B)

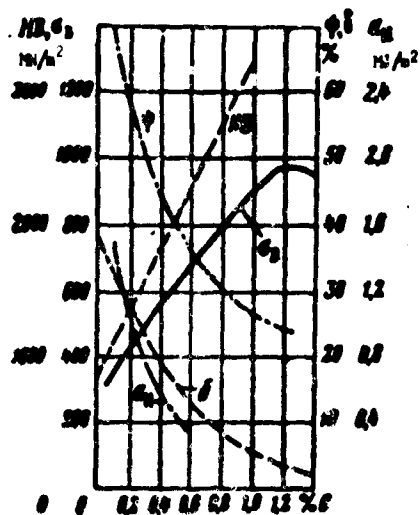


Fig. 10.1. Influence of carbon content on mechanical properties of steel.

are increased continuously with increase of carbon content to 1.2%; indices of ductility (δ, ψ) and impact toughness (α_H) simultaneously decrease. This change of properties is explained by change of quantity of cementite and ferrite in structure of steel with increase in it of carbon content.

With increase of quantity of carbon technological properties of steel are changed also. Forging of it in cold state is impossible and is hampered in hot state. Machinability is hampered, weldability worsens, but casting qualities are improved.

Influence of manganese and silicon. Presence in steel of manganese and silicon is caused by process of smelting steel. In order to be free of ferrous oxide, formed during melting and worsening properties of steel, manganese and silicon are introduced. This process is called deoxidation of steel. Here, manganese content must not exceed 0.75% and that of silicon 0.35%.

Content of silicon and manganese in such quantity has practically no influence on mechanical properties of carbon steels.

Higher content of these elements essentially changes properties of steel and affects its behavior during mechanical and heat treatment. Steels which contain more than 1% manganese and more than 0.8% silicon are called special steels.

Influence of sulfur and phosphorus. Sulfur and phosphorus are harmful impurities. Presence of more than 0.05% of each of these impurities sharply worsens quality of steel. Harmful action of sulfur consists in that it causes red-shortness in steel, i.e., raised brittleness (formation of cracks) in hot state during forging and rolling. Red shortness of steel is explained by the following: sulfur, combining with iron, forms eutectic whose melting point is equal to 985°C, much lower than melting point of steel. During crystallization of steel this eutectic is disposed on grain boundaries. And when steel is heated for forging or rolling eutectic melts,

connection between grains is broken, and steel becomes brittle.

Red-shortness is removed by addition of manganese to steel, which, combining with sulfur, forms manganese sulfide (its melting point is 1620°C).

Harmful action of phosphorus consists in sharp increase of brittleness of steel at normal temperature. This phenomenon is called cold-shortness. Cold-shortness of steel is due to fact that phosphorus, dissolved in ferrite, imparts high brittleness to steel at normal temperatures.

Harmful influence of phosphorus shows up more strongly with raised carbon content. However, in so-called automatic steels (with carbon content of up to 0.3%) raised content of phosphorus is allowed (to 0.15%) and of sulfur (to 0.2%) to facilitate removal of shavings and for obtaining smooth surface during machining, in particular during cutting of threads.

§ 2. Classification and Grading of Carbon Steels

Classification of Carbon Steels

According to method of production, we distinguish the following steels:

1) carbon steel of ordinary and raised quality, which is smelted in converters and large open-hearth furnaces; in these steels content of harmful impurities should be within the following limits; sulfur 0.05-0.09% and phosphorus 0.06-0.075%. In turn, carbon steel of ordinary and raised quality is divided into three groups:

I group - steel supplied with guaranteed mechanical properties;

II group - steel supplied with guaranteed chemical composition;

III group - steel of raised quality supplied with guaranteed chemical composition and mechanical properties;

2) quality steel smelted in basic open-hearth furnaces with observance of stricter requirements with respect to charge and the actual process; in these steels content of sulfur and phosphorus must not exceed 0.04% (each);

3) high-quality steel smelted in acid and basic open-hearth furnaces or in electric furnaces; this steel is distinguished by lowered content of harmful impurities (sulfur and phosphorus) up to 0.03% each.

Depending upon assignment of steel and its carbon content, we distinguish:

1) structural steels, intended for constructions and machine parts; these steels must possess sufficiently high complex of mechanical properties;

2) tool steels, intended for manufacture of tools of different assignment; these steels must possess high hardness and good cutting properties.

With respect to heat treatment, we distinguish steels:

- 1) not subjected to heat treatment; these include carbon steels of ordinary quality, applied in state of delivery;
- 2) carburized steels; these include low-carbon structural steels with carbon content to 0.3%;
- 3) improved steels; these include medium-carbon structural steels which contain from 0.35 to 0.55% carbon and are subjected to hardening and tempering.

According to degree of deoxidation, steels are divided into:

- 1) mild steel, which is deoxidized completely during smelting;
- 2) rimmed steel, which is deoxidized during smelting by manganese only.

Grading of Carbon Steels

Grade of steel is conventional designation which characterizes chemical composition, quality, content of separate elements, and in certain cases method production.

Structural carbon steels of ordinary and raised quality.

Steels of group I have following grades: St. 0, St. 1, St. 2, St. 3, [St. 3kp] (St. 3кп), St. 4, St. 5, St. 6, St. 7. Letters "St." denote steel and numbers 0, 1, 2, 3, etc. denote number of steel. With increase of number, ultimate strength (carbon content) increases. Letter ["B"] ("B") before grade indicates that steel is Bessemer, absence of letter means that steel is open-hearth. Grades of rimmed steel have at the end the index "kp"; absence of these letters signifies mild steel.

Steels of group II have following grades: B09kp, B09, B16, B23, B33, and M09kp, M12kp, M18kp, M18, M21, M26, M31, M44, M56. First letter shows method of smelting of steel (B - Bessemer steel, M - open-hearth steel), and figure shows average carbon content in hundredth shares of a percent.

Steels of group III have following grades: M09, M12, M16, M18a, [I21a] (M21a), M26a, M31a, M44a, M56a. These steels are graded like steels of group II, but to grade of steels this group is added letter "a," which indicates raised quality.

Quality and high-quality structural carbon steels. Structural carbon steels have following grades: 0.5, 0.5kp, 08, 08kp, 10, 10kp, 15, 20, 20kp, 25, 25kp, 30, 35, 40, 45, 50, 55, 60, 65, 70. Letters are not placed ahead of grade of these

steels: for instance, "steel 30" or "steel of grade 30." Two-digit figures in grade of steel denote average carbon content in hundredth shares of a percent. For example, steel of grade 15 contains on the average 0.15% carbon, steel 50-0.50% carbon, etc. Letters "kp" signify that steel is rimmed, i.e., is deoxidized during smelting by manganese only.

If to designation of grade of carbon steel is added letter "A," for instance, 15A, 20A, it signifies that given steel is high-quality, i.e., has minimum content of harmful impurities.

Besides pure-carbon steel, there is applied steel with raised manganese content - grades [15G] (15Г), 20G, 40G, 30G2, 40G2, 50G2, and others. In these grades letter "G" indicates raised manganese content (near 1%) and figure 2 after letter "G" signifies that in steel is about 2% manganese. Letter ["L"] ("Л") after grade indicates that steel is for casting.

Carbon tool steels. Quality tool steels have grades [U7] (Y7), U8, U8G, U9, U10, U11, U12, and U13; and high-quality grades are U7A, U8A, U8GA, U9A, U10A, U11A, U12A, and U13A. Letter "U" in designation of grade of steel denotes that this is carbon steel. Figure standing after letter "U" shows content of carbon in tenth shares of a percent. For instance, U7A designates carbon tool steel with 0.7% carbon. Letter "A" indicates that steel is high-quality, i.e., contains minimum quantity of sulfur and phosphorus.

§ 3. General Characteristics and Assignment of Carbon Steels

Structural Steels

Structural carbon steels contain from 0.05 to 0.75 and in special cases up to 0.85% carbon. Structural carbon steels of ordinary quality are supplied without heat treatment in the form of sheet and assorted rolled stock. They are applied for building structures and machines.

Structural carbon steels (quality and high-quality) possess sufficiently high complex of mechanical properties, but they do not always satisfy technical requirements. They are used for manufacture of less vital, comparatively lightly-loaded and nonloaded aviation parts.

In Table 5 are given chemical composition and mechanical properties of these steels.

Table 5. Chemical Composition and Mechanical Properties of Carbon Structural Steels

Grade of steel	Carbon content in %	Mechanical properties of normalized steels (not less)			HB hardness after annealing, MPa/mm ²
		ultimate strength σ_B , MPa/mm ²	elongation δ , %	reduction of area ψ , %	
08	0.05—0.10	300—450	33	60	—
10; 10A; 10k2	0.07—0.13	300—430	29	55	—
15; 15A	0.12—0.20	440—540	26	55	—
20; 20A	0.17—0.24	520—620	22	55	—
25	0.22—0.29	600—680	21	50	—
35	0.32—0.39	680—800	17	45	1430—1870
45; 45A	0.42—0.49	710—830	13	40	1970
50	0.47—0.55	800—950	12	40	2070
70 (BC, OBC)	0.67—0.75	1100	8	30	2290

Depending upon carbon content, quality structural steels are divided into low-carbon, medium-carbon, and high-carbon types.

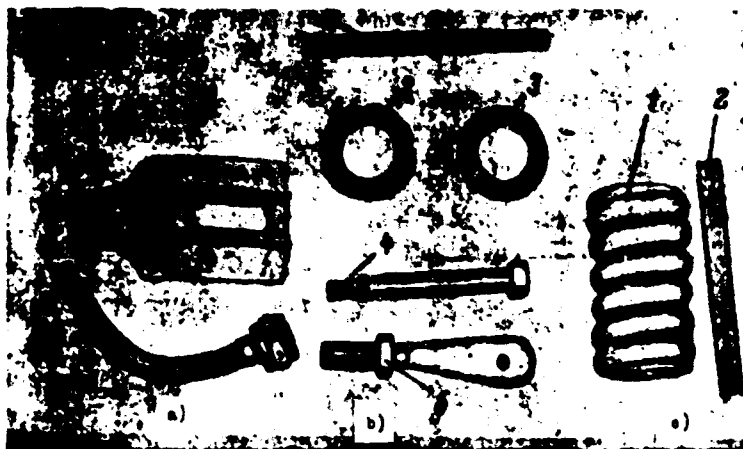


Fig. 10.2. Part made from carbon structural steels. a) parts of low-carbon steels. 1 - welded bracket of steel 20, 2 - section of line of hydraulic system of steel 20A, b) parts of medium-carbon steels. 1 - pin of engine crankcase, 2 - slotted nut, and 3 - casing of sealing rings of hydraulic system of steel 35, 4 - bolt for control rod of bracket for control of engines, prepared of steel 45, 5 - rod clevis for hydraulic cylinder, prepared of steel 45A, c) parts of high-carbon steels. 1 - coil spring of cylinder for emergency release of front gear of aircraft, prepared of steel 70, 2 - flat spring for holding clutch block of brake wheel, prepared of steel U8A.

In Fig. 10.2 are presented parts prepared from low-carbon (a), medium-carbon (b), and high-carbon (c) steels.

Low-carbon steels contain from 0.05 to 0.30% carbon. They possess low strength, high ductility, and good weldability. Low-carbon steels are applied in airplane industry mainly for lightly-loaded parts or parts during whose manufacture considerable plastic deformation is required. As a rule, these steels are applied without hardening.

Steel 08 has high ductility, allows deep stamping, complicated bending, knockout, welds excellently, and is supplied in the form of sheets and wire. It is applied in state of delivery for welded and stamped nonvital parts subjected to considerable plastic deformation.

Steels 10, 10kp, and 10A possess high ductility, weld well by all forms of welding, are carburized and cyanided, and allow deep stamping, complicated bending, knockout, etc. They are supplied in the form of rods, sheets, tubing, and wire. They are applied in annealed and normalized state for low-strength parts of aircraft and motors, prepared by welding, bending, or stamping: tanks, joints, bolts, nuts, washers, angles, frames, mesh, and rings.

For manufacture of carburized parts not experiencing considerable stresses but subject to wear steel 10 is applied. Steel 10kp is used for manufacture of parts by means of deep stamping, for instance, housings for combustion chambers of jet engines. Wire of steel 10A is applied as filler material during welding of joints and parts.

Steels 15 and 15A have high ductility and weld well by all forms of welding. They are supplied in the form of wire and are applied mainly for manufacture of rivets with low shear resistance.

Steels 20 and 20A are well suited to cold plastic deformation, weld well by arc and resistance welding, and can be subjected to carburizing, carburizing, and cyaniding. They are supplied in the form of sheets and tubing. These steels are applied basically in annealed or normalized state for welded and stamped parts with low strength: shoes, joints, corner plates, brackets, levers, rockers, collars, main oil lines, sealing rings, of flanges of fittings, hose tips, housings of solenoids, packing washers, transition flanges of gas collectors, and others. Tubing is applied for manufacture of tubular rivets and also lines for hydraulic air brake and other systems.

Steel 25 welds well by arc and resistance welding. It is supplied in the form of rods, wire, and forgings. This steel is applied mainly in annealed or normalized state for lightly-loaded parts: bolts, nuts, screws, nipples, tubes, plugs, bushings, suspension joints, and others.

Medium-carbon steels contain from 0.32 to 0.55% carbon. They possess medium strength, satisfactory ductility, and good machinability. In aviation industry medium-carbon steels are used for mechanically processed parts. As a rule, these steels are applied in normalized or annealed state. When these steels are used for manufacture of medium-loaded parts, they are improved (hardening with high temper).

Steel 35 machines well. It is welded satisfactorily by all forms of welding. It is supplied in the form of rods, tubing, sheets, and forgings. This steel is applied in normalized state and also, after hardening with tempering, for welded and mechanically processed parts such as shafts, suspension joints, bolts, nuts, washers, and others.

Conditions of heat treatment: annealing and normalization from temperature of 850-900°C, hardening from 850-870°C, cooling in water or oil, high tempering.

Steels 45, 45A, and 45L machine well. They are welded satisfactorily by arc and unsatisfactorily by gas.

Steel 45 in annealed, normalized, and work-hardened states is used for manufacture of lightly-loaded machined parts: bolts, pins, plugs, nuts, unions, tees, housings of stuffing boxes, and others. Parts of steel 45 can be subjected to heat treatment. Conditions of heat treatment: annealing and normalization at 850°, hardening from 820°C in oil.

Steel 45A is used for ribbon braces, shafts and their couplings. Heat treatment: temperature of heating before hardening (in oil), annealing, and normalization is 840-860°C.

Steels 45 and 45A are supplied in the form of rods, tubing, sheets, wire, and forgings.

Steel 45L is used for shaped castings. In annealed state machinability is good. Conditions of heat treatment: hardening from 840-850°C, tempering to required strength. It is used for manufacture of castings of lightly-loaded parts, brackets, turret rings, and others.

Steel 50 machines well and possesses satisfactory ductility. It is supplied in the form of rods and tapes and is applied in normalized state and also, after hardening with temper, for flat springs and mechanically processed parts. Conditions of heat treatment: annealing, normalization, and hardening at a temperature of 790-810°.

High-carbon steels contain from 0.60 to 0.75% carbon. They possess great strength, high elastic and fatigue limits. High carbon steel has found wide application in the form of tapes and wire for manufacture of flat and coil springs.

We distinguish wire of high resistance [VS] (RC) and specially high resistance [OVS] (OBC); they belong to the same grade - high-carbon steel 70.

Heat treatment of wound springs made from cold-drawn wire consists in tempering at 260-300°, after which steel, depending upon diameter of wire, is characterized by ultimate strength of 1400-2650 MN/m² (140-265 kgf/mm²).

Besides this, for manufacture of different flat springs are applied tapes of high-carbon steels of grades U8, U8A, U9, and U9A.

Conditions of heat treatment of these springs: hardening from temperature of 770-790°C in oil and tempering at 350-420°C; after which they have HRC hardness of 44-48.

For manufacture of semivital parts (bolts, nuts, screws) prepared on automatic machines are applied so-called automatic steels. They machine well and can be processed at high speeds. High workability of automatic steels and good quality of surface are due to raised content of sulfur and phosphorus. Chemical composition and mechanical properties of automatic steels are given in Table 6.

Table 6. Chemical Composition and Mechanical Properties of Automatic Structural Steels

Grade of steel	Chemical composition in %					Mechanical properties (not less)	
	C	Si	Mn	P not more	S	σ_b MN/m ²	δ %
A12	0.08-0.15	0.15-0.35	0.60-0.90	0.08-0.20	0.08-0.15	420-800	7-22
A20	0.15-0.25	0.15-0.35	0.60-0.90	0.06	0.08-0.15	460-820	7-20
A30	0.25-0.35	0.15-0.35	0.70-1.00	0.06	0.08-0.15	520-840	6-15

In grades of steel letter A denotes automatic, figure indicates average carbon content in hundredth shares of a percent. Automatic steels are supplied in hot-rolled and in cold-drawn states in the form of rods.

Tool steels. Carbon tool steels contain from 0.6 to 1.4% carbon; as compared to structural steels, they have higher strength and hardness and lower ductility. They are designed for manufacture of cutting, measuring, and stamping tools. For manufacture of tools steels are supplied in the form of rods, tapes, wire, forgings, and so forth. For good workability carbon tool steels have to be well annealed. Finished tool is subjected to hardening and tempering. Temperature of hardening is selected from iron-carbon constitutional diagram and that of temper is selected in dependence upon assignment of tool and required hardness.

Carbon tool steels have high critical rate of hardening and low hardenability (10-12 mm); therefore it is recommended that they be applied for tools of small cross section.

Merits of carbon tool steels include: low hardness, good machinability and pressure workability in annealed state, and also high impact and vibration strength due to preservation of ductile core as result of low hardenability.

Carbon tool steels have the following deficiencies: narrow interval of tempering temperatures; necessity for carrying out sharp hardening, what involves considerable deformations and warping of tool. Tool of carbon steel is unfit for treatment of strong and hard alloys, cannot be used for treatment at high speeds or rapid feed. Therefore on contemporary highly productive machines of basic application are tools of special and high-speed cutting steels.

Properties and application of carbon tool steels, and also conditions of heat treatment, depend mainly on their carbon content.

In Fig. 10.3 are given samples of cutting (a) and measuring (b) tools made from carbon tool steels.

Approximate assignment of various grades of carbon tool steels are:

Steels U7 and U7A (0.65-0.74% C) - for tools subjected to blows and shocks and requiring considerable ductility, with moderate hardness: centers of machine lathes, chisels, set dies, sledge hammers, forging and metal-working hammers, stamps, and others.

Steels U8 and U8A (0.75-0.84% C) - for tools subjected to blows and requiring good ductility with high hardness: dies, punches, shears and knives for metal,

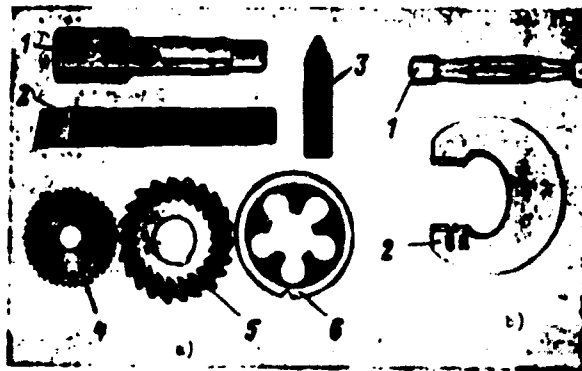


Fig. 10.3. Tools made from carbon steel.
a) cutting tools: 1 - end-milling cutter, 2 - through cutter, 3 - thread cutter, and 6 - machine screw die from steel U10; 4 - groom-milling cutter and 5 - conical milling cutter of steel U12. b) measuring tools: 1 - bore gauge and 2 - outside caliper of steel U13.

carpenter's and pneumatic tools, and others.

Steels U9 and U9A (0.85-0.94% C) - for tools requiring hardness in the presence of certain ductility punches, hole punching dies, and others.

Steels U10 and U10A, U11 and U11A (0.95-1.09% C and 1.05-1.14% C) - for tools not subjected to strong blows, with high hardness on cutting edge: cutters, drills, taps, screw dies, reamers, milling cutters, blades, shaping dies, and others.

Steels U12 and U12A, U13 and U13A (1.15-1.24% C and 1.25-1.35% C) - for tools not subjected to blows and requiring hardness: lathe and planing cutters, files, scrapers, gauges, razors, drawing tools, and others.

CHAPTER XI

ALLOY STEELS AND SPECIAL ALLOYS

§ 1. Concept of Alloy Steels

Alloy steel is that in which for production of required properties alloy elements are specially introduced: chromium, nickel, manganese, silicon, tungsten, molybdenum, vanadium, cobalt, titanium, niobium, aluminum, and others. Manganese and silicon, present in steel as constant impurities, are considered alloy components only when content of manganese is more than 1% and that of silicon is more than 0.9%.

Alloy elements introduced in steel change its mechanical or physicochemical properties. Basic advantages of alloy steel are revealed only after its heat treatment. Series of alloy steels does not change microstructure during heat treatment. Such steels are hardened by means of plastic deformation.

By alloying it is possible to increase considerably strength and hardness, preserving under known conditions satisfactory and good ductility.

Alloying of steel increases its hardenability and also makes it possible to produce hardening to martensite in moderate coolants, which decreases danger of appearance of cracks and warping of parts.

By alloying it is possible to give steels a series of special properties, such as heat resistance, resistance to scaling, acid resistance, and others.

Alloy steels are widely applied in aviation industry.

§ 2. Influence of Alloy Elements on Properties of Steel

Properties of steel during alloying are changed in dependence upon quantity of introduced alloy elements and character of their interaction with iron and carbon.

Alloy elements can be dissolved in ferrite to form carbides and chemical compound with iron.

Alloy elements affect phase transitions occurring in steel on character of its structure and on its properties.

Influence of alloy elements on allotropy of iron. Alloy elements, being dissolved in iron, influence position of critical points A_3 and A_4 , and consequently region of existence of α - and γ -iron. One group of alloy elements expands region of γ -solid solutions of constitutional diagram of iron-alloy element system, other group narrows this region.

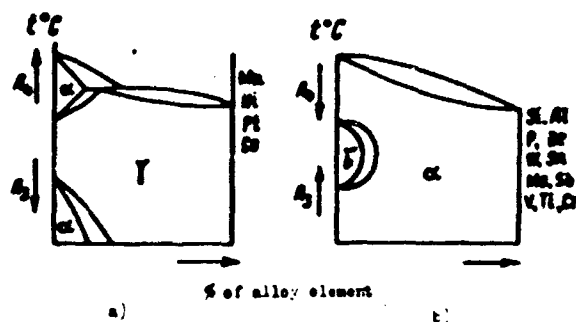


Fig. 11.1. Influence of alloy elements on allotropic transformations in iron. a) open domain of γ -iron, b) closed domain of γ -iron.

To first group belong nickel, manganese, carbon, copper, and nitrogen. They lower critical point A_3 and raise point A_4 , i.e., form with iron expanded γ -region (Fig. 11.1a). With large quantity of these elements alloys will not have allotropic transformations and austenite will be stable even at room temperature. Such alloys are called austenitic.

To second group pertain silicon, chromium, aluminum, molybdenum, tungsten, vanadium, titanium, boron, zirconium, and phosphorus. They increase critical point A_3 and lower point A_4 , i.e., form with iron closed γ -region (Fig. 11.1b). With large quantity of these elements alloys also will not have allotropic transformations, region of γ -iron will be suppressed and at any temperature structure of steel will consist of α -solid solution. Such steels are called ferrites.

Solubility of alloy elements in iron. As alloy additions there most frequently are applied elements capable of dissolving in iron. Solubility of majority of alloy elements in iron promotes small difference in atomic radii and similarity of crystal lattices.

Only elements with very small atomic radius (B, C, N, O, H) form with iron solid solutions of introduction of small concentration. All remaining elements dissolved in iron (Si, Ni, Co, Mn, Cr, Mo, W) form substitutional solid solutions.

Alloy elements, being dissolved in iron, change its properties: increase ultimate strength, yield point, hardness and lower ductility. Atoms of alloy elements, differing from iron atoms in dimensions and structure, create stresses in crystal lattice, causing changes in its parameters. Parameter of lattice is changed more the greater the difference between atomic dimensions of iron and alloy element.

Change of dimensions of crystal lattice of iron and causes considerable change of its properties. Alloy elements, having the same crystal lattice as ferrite and differing little in dimension from atoms from iron, strengthen ferrite insignificantly. Such elements include chromium, molybdenum, and tungsten. Conversely, elements having crystal lattice differing from ferrite sharply differ from iron in physicochemical properties and strengthen ferrite more than any others. These elements include manganese.

Ductility of ferrites below that of molybdenum, tungsten, manganese, and silicon. This is explained by large distinction in dimensions of atomic radii of iron and these alloy elements.

The most valuable element is nickel. It increases strength of ferrite and consequently strength of steel without lowering of its ductility and toughness. In ferrite is dissolved up to 25-30% nickel, where content of carbon in steel does not practically affect magnitude of maximum solubility of nickel in ferrite.

Nickel also increases toughness of structural steels, where the greater it is the less carbon is contained in steel.

Other elements even if not lowering toughness of ferrite, do increase its strength (chromium) or strongly increase strength, sharply lowering toughness (manganese and silicon).

Essential influence on mechanical properties of steel is rendered by its microstructure, which can be changed qualitatively through increased content of alloy elements. For instance, chromium little affects properties of steel in perlitic state but sharply increases strength of steel in martensite state.

Ratio of alloy elements to carbon. Depending on ratio of carbon, behavior of alloy elements can be different. According to ratio of carbon, alloy elements are

divided into two groups: carbide-forming and graphite-forming.

Carbide-forming elements are those which with carbon of steel form carbides - chemical compounds stabler than carbide of iron. They include the following elements: niobium, titanium, vanadium, tantalum, molybdenum, tungsten, chromium, manganese, and iron. These carbide-forming elements fall, according to degree of their affinity for carbon, in diminishing series. This means that niobium is the strongest carbide-forming element and iron is the weakest.

Carbide-forming elements can be dissolved in small quantity in cementite, forming alloyed cementite. Alloy elements can form simple carbides, for instance, Cr_4C , WC , TiC , and others, and complex (double) carbides, for instance, $(\text{Fe}, \text{Cr})_4\text{C}$, $(\text{Fe}, \text{W})_6\text{C}$, and others. Carbides formed by alloy elements are harder and more wear-resistant than carbide of iron (cementite). Role of carbides in forming of properties of steel is very great, since very many changes of properties of steel are connected with processes of dissolution, precipitation, or coagulation (enlargement) of carbide phase.

Elements which do not form carbides with carbon and lower stability of carbides of other elements form group of graphite-forming alloy elements. These elements include silicon, aluminum, nickel, and cobalt. They are arranged according to diminishing degree of graphitizing. Interacting with iron, these elements form solid solutions, and consequently are in ferrite or austenite.

Influence of alloy elements on heat treatment of steel. Alloy elements change position of critical points with respect to their position for carbon steel. This has large value during determination of temperature of heating of alloy steels for their heat treatment. Elements narrowing γ -region increase temperature of eutectoid transformation, and elements expanding γ -region lower it. Obviously, for steels alloyed with elements narrowing γ -region temperature during heat treatment is higher than for carbon steels. For steels alloyed with elements expanding γ -region temperatures reached before heat treatment will be lowered. Besides this, all alloy elements decrease concentration of carbon in perlite.

Essential influence on growth of grains of austenite during heating of steels is rendered by alloy elements. All alloy elements, with the exception of manganese, decrease inclination of austenite to grain growth when heated. Elements not forming carbides, and consequently being in solid solution during formation of austenite,

weakly influence this inclination. Carbide-forming elements strongly prevent growth of grains of austenite. We consider that carbides not dissolved in austenite mechanically prevent growth of grains of austenite. Analogously to carbide-forming elements, growth of grains of austenite is influenced by elements forming stable oxides (aluminum, silicon, titanium, and vanadium).

Very large influence is rendered by alloy elements on isothermal disintegration of austenite. All alloy elements, with the exception of cobalt, in this or that degree increase stability of austenite, shifting curves of isothermal transformation to the right.

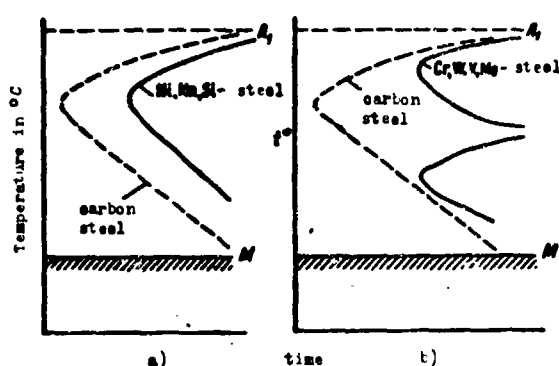


Fig. 11.2. Diagrams of isothermal disintegration of austenite. a) carbon steel and steel alloyed with noncarbide-forming elements, b) carbon steel and steel alloyed with carbide-forming elements.

Character of isothermal disintegration of austenite during cooling of alloy steels differs from character of disintegration of austenite of carbon steels. Noncarbide-forming elements and also manganese, shifting diagram of isothermal disintegration of austenite, does not change its character. With alloying by carbide-forming elements, on diagram of isothermal disintegration of austenite appears second maximum (Fig. 11.2). Thus for these steels in interval of temperatures between two maxima austenite possesses very great stability. The greatest stability of austenite is noted at 500-600°C, i.e., in this interval of temperatures, where steels alloyed with noncarbide-forming elements have stability of austenite. Therefore simultaneous alloying of steel with elements of both groups permits obtaining high stability of austenite.

However, carbide-forming elements increase stability of austenite only in that case when they are dissolved in it. Carbides outside solution of austenite lower

its stability. Increasing stability of cooled austenite, alloy elements strongly lower critical rate of hardening and increase hardenability (exception is cobalt). Therefore alloy steels are hardened at slower rate of cooling. This permits application as liquid coolant of oil (instead of water) and the obtaining of raised mechanical qualities for parts of considerable dimensions. Hardenability is especially strongly increased by molybdenum, manganese, chromium, and nickel. Hardenability of steel is influenced in strong degree by small additions of boron (about 0.004%).

Majority of alloy elements (besides Al and Co) lowers temperatures of martensite transformation and increases quantity of residual austenite. The biggest influence on martensite point is rendered by manganese, chromium, and nickel. With sufficiently large content of these elements, temperature of beginning of martensite transformation can fall below zero. In such steels at room temperature austenitic structure can be obtained. Temperature of end of martensite transformation also is lowered by majority of alloy elements, but less energetically than temperature of beginning of transformation.

Alloy elements not forming carbides affect character of change of hardness during tempering. Carbide-forming elements change condition of transformations during tempering. Alloying of steel with carbide-forming elements delays process of disintegration of martensite. Therefore in order during tempering to lower hardness to assigned limit it is necessary to heat alloy steel to higher temperature or to give more time to tempering than for carbon steel.

Owing to the fact that alloy elements decrease thermal conductivity of steel, alloy steels during heat treatment must be heated and cooled more evenly and slowly. Otherwise considerable internal stresses are formed, which can lead to cracks and warping of article.

Characteristics of influence of alloy elements. So as to make correct selection of steel for different articles it is necessary to know the influence on its properties rendered by most important alloy elements.

Chromium - cheap element, widely applied in alloy steels. In structural steels it is contained in quantity up to 3%. It increases hardness and strength of steel and simultaneously insignificantly lowers ductility and toughness. Presence of chromium increases hardenability of steel. Thanks to high wear-resistance of chromium steels, from it are prepared antifriction bearings. Chromium is introduced

into composition of high-speed cutting steels. With chromium content of over 13% steel becomes rust-resistant. Further increase of chromium content imparts oxidation resistance to steels at high temperatures. Chromium also imparts stability of magnetic properties to steel.

Nickel - costly alloy element. Due to its high cost it is applied only in those cases when it is impossible to replace it by a cheaper element. In structural steels is contained from 1 to 5% nickel. It gives steels strength, high ductility, and toughness. Large nickel content is used in those cases when it is necessary to obtain nonmagnetic steel and raised corrosion resistance. For alloying of tool steels nickel is not applied.

Tungsten - costly alloy element. Present in small quantities in structural steels (not over 1.5%). It increases hardness and strength of steel and promotes formation of fine-grained structure. Tungsten in raised quantities (not more than 22%) is introduced into tool steel for improvement of cutting properties and is indispensable addition in high-speed cutting steels. Presence of tungsten is desirable in heat-resisting steels.

Molybdenum - scarce element. Present in small quantities in structural steels (0.2-0.6%). Increases strength and hardness of steel, insignificantly lowers ductility and toughness, and decreases temper brittleness. In tool (high-speed cutting) steels molybdenum increases red hardness. The most valuable property of molybdenum is that it imparts heat resistance to steels.

Vanadium is introduced in small quantities into structural steels (0.1-0.3%), tool steels (0.15-0.65%), and high-speed cutting steels (up to 2.5%). It increases hardness of steel and gives it fine-grained structure with raised elasticity and fatigue strength.

Manganese - cheap alloy element. An inevitable impurity introduced into steel for deoxidation. It is considered an alloy element if its content is higher than 1%. In structural steels it is present in not more than 2%. Manganese promotes deep hardenability of steel and improves its mechanical properties. Raised content of manganese gives steels wear-resistance and makes it nonmagnetic.

Silicon - accessible and cheap element. It is like manganese, an inevitable impurity of steel, introduced for deoxidation.

In structural steels it is contained in up to 2%, it increases strength and

elasticity of steel while preserving toughness (in spring steels). Raised content of silicon in steel, up to 2-4%, increases its electrical resistance and magnetic permeability.

Niobium and titanium are added to steel in small quantities (0.1-0.2%). In rust-resistant chromium-nickel steels they prevent appearance intercrystalline corrosion. They promote fine-grained structure, favorably reflected in mechanical properties of steel.

Aluminum is introduced into steel subjected to nitriding to increase hardness. Besides this, with content of 5-6% it imparts resistance to scaling to steels. Aluminum in 12-15% is introduced into alloys going to manufacture of permanent magnets with high magnetic properties.

Boron in very small quantities (to 0.002%) considerably increases hardenability of steel. Presence of boron increases resilience of steel after low tempering. Even 0.01% boron in heat-resisting alloys increases their heat resistance.

§ 3. Flaws in Alloy Steels

In alloy steels can appear the following flaws: dendritic liquation, flakes, temper brittleness, and slaty fracture.

Dendritic liquation of alloy steels consists in that during slow cooling of ingot there first hardens solid solution impoverished of carbon and alloy elements, and then in interdendritic spaces occurs formation of crystals richer in carbon and alloy elements. Dendritic liquation is due to the fact that in alloy steels temperature interval of crystallization is great. And since diffusion rate of alloy elements in steel is low, dendritic liquation is preserved. After being rolled, such

steel frequently takes on characteristic banded structure (Fig. 11.3), which imparts to it different properties with and across direction of rolling, lowers strength, and worsens workability. It is possible to decrease dendritic liquation by prolonged diffusion annealing of ingot before they are rolled.

Flakes are very dangerous flaw in alloy steel. Flakes are very small internal cracks revealed in break of alloy steels in the form of white spots (Fig. 11.4).



Fig. 11.3. Banded structure of steel.

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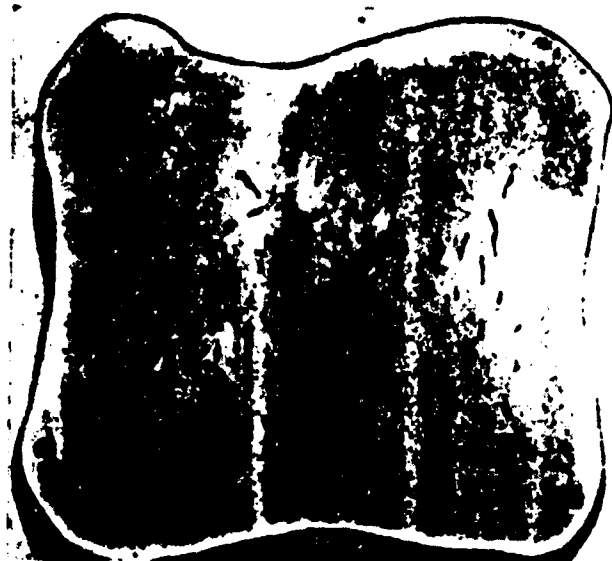


Fig. 11.4. Flakes in chrome-nickel steels.

Most subject to formation of flakes are steels containing chromium. Flakes strongly lower impact strength of steel and its resistance to variable loads.

Flakes can be formed in steel owing to appearance of high internal stresses, provoking cracks. Cause of appearance of such high internal stresses can be accumulation of liberated hydrogen, dissolving in liquid steel. During fast cooling after rolling or forging hydrogen liberated as result of lowering of solubility is not able to diffuse from internal layers, are created bubbles with high internal pressure, which leads to breaks. In addition to this, cracks in ingot can be formed as a result of appearance of internal stresses during nonsimultaneous phase transitions in connection with heterogeneity of steel.

To prevent appearance of flakes is possible by melting steel under conditions preventing entry of hydrogen. For decrease of formation of flakes it is expedient to apply slow cooling of ingots, during which hydrogen absorbed by steel departs from it without causing breaks. Steel in which flakes already have formed is corrected by rolling to small profiles or by applying large forging reduction ratio, resulting in welding of cracks.

Temper brittleness. Many alloy steels (chrome-nickel, chrome-manganese) display sensitivity to method of cooling after high tempering. Through slow cooling after high tempering they obtain very considerable brittleness, which is not observed under conditions of rapid cooling.

Supposed cause of temper brittleness is precipitation of small carbides on

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Fig. 11.5. Slaty fracture steel.

grain boundaries during slow cooling of steel after tempering in interval of 500-600°.

Steels sensitive to temper brittleness must be cooled rapidly after high tempering. Additional alloying of these steels with molybdenum also removes temper brittleness.

Slaty fracture - laminar structure of steel

(Fig. 11.5). Such steel possesses raised brittleness.

Slaty fracture appears after hot pressure working in accordance with place of structural location of defects. The less harmful impurities and blowholes in ingot the less the probability of formation of slaty fracture.

§ 4. Classification and Grading of Alloy Steels

Classification of Alloy Steels

Alloy steels are classified according to four criteria: chemical composition, assignment, structure in annealed state, and structure after cooling in air.

Classification by chemical composition considers those elements besides iron and carbon and in what quantities they exist in steel.

Depending upon quantity of alloy elements, we distinguish ternary, quaternary, and complex-alloy steels.

Ternary steels contain iron, carbon, and one alloy element; quaternary alloys contain iron, carbon, and two alloy elements; and complex-alloy steels contain three and more alloying elements.

Depending upon what elements are present in steel, it is called, for instance, chromium, manganese, chromium-manganese, chrome-nickel, chromium-manganese-silicon, and so forth.

Depending upon total content of alloy elements, we distinguish: low-alloy steels, with total content of alloy elements not higher than 3%; medium-alloy steel, with total content of alloy elements of from 3 to 10%; and high-alloy steel, with total content of alloy elements higher than 10%.

Classification by assignment considers criterion of application of steels. According to assignment alloy steels are divided into three basic classes: structural, tool, and steel of special assignment.

Structural steel is intended for manufacture of machine parts. Of structural steels is required good complex of mechanical properties.

Tool steels are applied for manufacture of tools of different assignment: cutting, measuring, stamping, and others. Of tool steels is required mainly hardness and wear-resistance.

Steels of special assignment are designed for special purposes. They include steels with any sharply expressed property. For instance, stainless steel is evaluated according to chemical stability; heat-resisting steel is evaluated according to mechanical strength at high temperatures; transformer steel is evaluated according to energy losses to polarity reversal, etc.

Classification according to structure in annealed state considers those structures of steel in equilibrium state. In accordance with this criterion alloy steels are divided into the following classes: hypoeutectoid, hypereutectoid, and ledeburite.

Hypoeutectoid steels contain free ferrite in their structure. Hypereutectoid steels have excess carbides in their structure. Ledeburite steels contain primary carbides in their structure, separated from liquid steel.

It is necessary to consider that for alloy steels boundary between hypoeutectoid and hypereutectoid steels on the one hand and hypereutectoid and ledeburite steels on the other hand corresponds to smaller content of carbon than in carbon steels. This is explained by the fact that the majority of alloy elements displaces points S and E of iron-carbon constitutional diagram toward smaller concentrations of carbon. Thus, carbon steels containing less than 0.8% carbon belong to hypoeutectoid class and those containing more than 2% carbon belong to ledeburites. With 5% chromium steel with 0.6% carbon content will be hypereutectoid and steel with 1.5% carbon content will be ledeburite.

Besides this, steels of ferrite and austenitic classes are also possible.

With small content of carbon and high content of alloy element, narrowing γ -region (chromium, tungsten, molybdenum, vanadium, silicon, and others), ferrite steels are obtained, having only structure of α -solid solution.

With high content of alloy elements, expanding γ -region (nickel, manganese, and others), austenitic steels are obtained, having only structure of γ -solid solution.

Classification by structure after cooling in air considers what structures are taken by steel samples of small cross section after normalization. According to this criterion alloy steels are divided into three basic classes: perlite, martensite, and austenite. This classification is very important, since structure of steel uniquely determines its properties. Thus, steel having perlitic structure possesses low hardness and high ductility, and steel having martensite structure is very hard and brittle. The first well and easily machines, the second is difficult to machine and responds poorly.

Formation of these classes of steel is determined by stability of cooled austenite. The greater the content of alloy element in steel the greater the

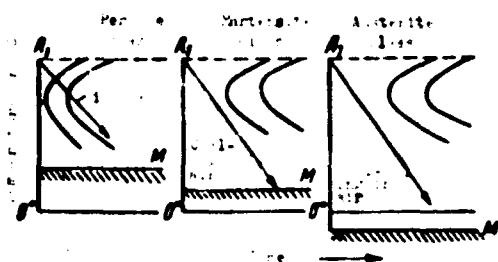


Fig. 11.6. Diagrams of isothermal disintegration of austenite for three classes of steels.

stability of cooled austenite and the lower the temperature of martensite transformation. Therefore for the same rate of cooling (in air) in steels of equal composition are formed different structures: mixtures of ferrite with cementite, martensite, or austenite.

In Fig. 11.6 are depicted diagrams of isothermal disintegration of austenite for steels of various classes. From diagram one may see how curves of cooling rate having the same slope, depending upon how far to the right C-shaped diagrams are shifted, intersect them at various temperatures, which also determines structure of disintegration of austenite.

Steels of perlite class contain comparatively small quantity of alloy elements (not more than 1-2%). After cooling in air, austenite in these steels disintegrates in region of high temperatures, with formation of ferrite-cementite mixture (perlite, sorbite, or troostite). To this class belongs the overwhelming majority of structural and tool steels.

Steels of martensite class contain raised quantity of alloy elements, expanding γ -region (Mn, Ni). These elements shift diagram of isothermal transformation to the right, so that austenite is cooled to martensite point.

After cooling in air structure, steels are all get martensite, in which can be included excess carbides. Application of these steels is small.

Steels of austenitic class contain up to 10-12% alloy elements (basically Ni, Cr, Mn). Owing to high stability of austenite at room temperature, martensite point in

region of negative temperatures, cooling in air leads to preservation of austenite at room temperature (see Fig. 11.1a). These steels include chrome-nickel stainless steels, certain heat-resisting steels, high-manganese wear-resisting steels, and other steels with special properties.

Steels containing large quantity of ferrite-forming elements with small carbon content can be placed in ferrite class (see Fig. 11.1b).

Besides this, steels having primary carbides in their structure, independently of structure of metallic base, frequently are called carbide or ledeburite steels. They have in their composition considerable quantity of carbon and carbide-forming elements (Cr, W, V, Mo).

Alloy steels, depending upon form of heat treatment, are additionally divided into carburized and improved steels.

Carburized steels contain up to 0.25% carbon and one or several alloy elements, promoting hardening during carburizing (Ni, Cr, Mn, W).

Improved steels are hardened and given high temper (thermal improvement), they contain average quantity of carbon (0.25-0.45%) and such alloy elements as nickel, chromium, tungsten, and molybdenum.

Also encountered is classification of steel in accordance with technological criterion. Basis for this is workability of steel by some method. According to this classification, steels are divided into deformable, casting, machinable, heat-treatable, and others.

Considered types of classification of steel are tightly interconnected. Thus, the same steel can be: low-alloy, chromium, structural, perlite, hypoeutectoid, forge, or improved.

Grading of Alloy Steels

Designation of grades of alloy steels follows literal-digital system. Alloy elements are designated by following letters: nickel [Ni] (N), chromium [Cr] (X), tungsten [W] (B), vanadium [V] (G), molybdenum [Mo] (M), titanium [Ti] (T), cobalt [Co] (K), silicon [Si] (C), manganese [Mn] (F), aluminum [Al] (L), copper [Cu] (E), niobium [Nb] (B), boron [B] (P), phosphorus [P] (H).

Every grade consists of combination of figures and letters. First figures of grade of steel denote average content of carbon in hundredth shares of a percent. Figures following letters indicate average content of given element in steel in

whole percents if its content exceeds 1.5%.

Letter A at the end of grade indicates high quality steel (purity with respect to harmful impurities) and high requirements of metallurgical control.

For instance, steel [30KhGSA] (30XГСА), on the average, contains 0.30% carbon, 1% chromium, 1% manganese, 1% silicon, 0.03% sulfur, and 0.03% phosphorus.

If ahead of grade is one figure, it indicates carbon content in tenth shares of a percent. For instance, steel 2Kh18N9 contains 0.2% carbon, 18% chromium, and 9% nickel.

If there are no figures ahead of grade, carbon in steel, on the average, is 1% or more. For instance, steel KhV5 contains 1.25-1.5% carbon, about 1% chromium, and about 5% tungsten.

In separate cases simplifications in designation steel are allowed, certain figures being omitted. For instance, instead of 18Kh2N4VA, we write simply 18KhNVA.

Certain high alloy steels are divided into special groups and are designated by letters placed ahead of designation: [Zh] (Ж) chromium stainless steels, [Ya] (Я) chrome-nickel stainless steels, [Ye] (Е) electrical steels with special magnetic properties, P high-speed cutting steels, [Sh] (Ш) ballbearing steels. For instance, steels Zh1, Ya1, Ye12, P18, and ShKh15.

Steels smelted at "Elektrostal" factory are designated by letter [E] (Э), those smelted in the same place as experimental grades are designated by letters [EI] (ЭИ) and a reference number. For instance, EI402, EI618, etc.

§ 5. Structural Alloy Steels

Structural steels are applied for manufacture of machine parts and mechanisms. On basis of conditions of their work, they have to possess complex of high mechanical properties: high strength, for resistance to large static loads; high ductility and toughness, for resistance to dynamic impacts; high endurance limit, for resistance to sign-alternating loads.

For parts of vital assignment are applied structural alloy steels possessing high mechanical properties and hardenability than carbon steels.

The biggest increase of mechanical properties is attained as a result of addition of several elements simultaneously. Best effect is given by alloying steels with elements in following combinations: Ni + Cr; V + Cr; Ni + V; Ni + Cr + V; Ni + Cr + W; Mn + Cr + Mo; Mn + Cr + Ti.

Here, it is necessary to consider that manganese, silicon, and chromium are cheap elements and nickel and molybdenum are scarce.

Best combination of properties of alloy steel is revealed after heat treatment; therefore machine parts prepared from alloy steel must be strengthened by heat treatment.

Most frequently structural steels are hardened in oil with subsequent high or low tempering. For certain steels good combination of strength and toughness is obtained as a result of isothermal hardening at a temperature of 300-400°C.

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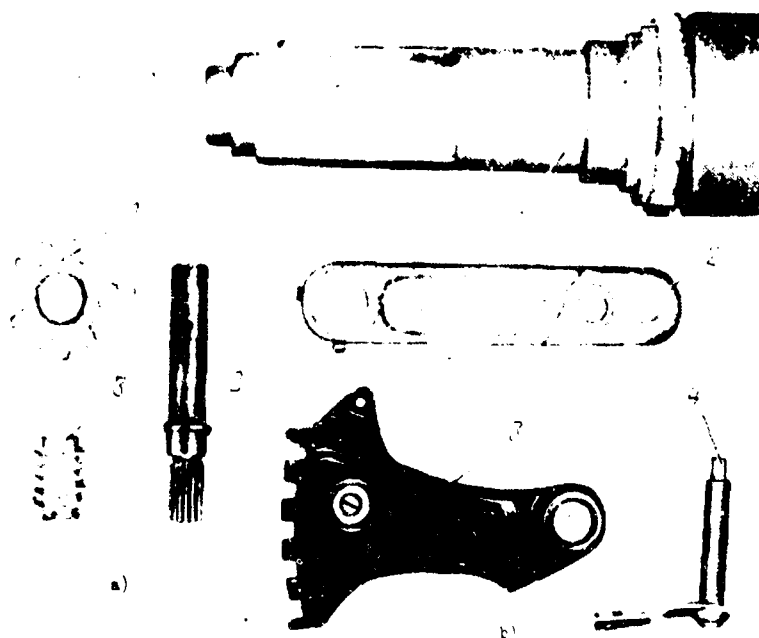


Fig. 11.7. Parts made from structural steels.
a) carburized parts. 1 - oil pump gear, 2 - splined drive shaft of aircraft generator, and 3 - worm reduction gear for flap-limit switch of steel 12KhN3A;
b) improved parts. 1 - shaft of gas turbine of jet engine of steel 40KhNMA, 2 - rocker of aileron control, 3 - toothed sector of elevator control, 4 - handle of landing-flap hoist of steel 30KhGSA.

In Fig. 11.7 are presented samples of parts made from structural alloy steels.

Let us consider the most important structural alloy steels.

Ternary Alloy Steels

Ternary alloy steels include steels containing, besides iron and carbon, one more alloy element. For instance, addition of nickel gives nickel steels, addition of chromium gives chromium steels, etc.

Nickel steels have high strength, considerable ductility and toughness, and good productibility (are processed well by pressure and cutting).

Chemical composition of nickel steels is characterized by content of nickel from 1.2 to 5.5% and carbon from 0.1 to 0.4%.

Low-carbon nickel steels, containing up to 0.15% carbon, are carburized. They include steels 13N2A (0.10-0.16% C; 0.3-0.6% Mn; 1.7-2.2% Ni), 13N5A (0.10-0.17% C; 0.3-0.6% Mn; 4.5-5.5% Ni), and others.

These grades are used for manufacture of camshafts, cam discs, and lightly-loaded parts.

Owing to scarcity of nickel, nickel steels find limited application.

Chromium steels have high strength and hardness after heat treatment, are cheap, and find wide application. Chromium is strong carbide-forming element. Property of chromium to increase hardness of steel is utilized in high-carbon bearing steels. In Table 7 are given approximate chemical composition and mechanical properties of the most common chromium steels.

Table 7. Chemical Composition and Mechanical Properties of Chromium Steels

Grade	Chemical composition in %				Mechanical properties (not less)		
	C	Si	Mn	Cr	σ_B MN/m ²	δ %	a_K MJ/m ²
15XA	0.12-0.17	0.17-0.37	0.30-0.60	0.70-1.00	600-700	11-15	0.9
35XA	0.34-0.42	0.17-0.37	0.50-0.80	0.80-1.10	900-950	12	0.9
ШХ15	0.95-1.10	0.15-0.35	0.20-0.40	1.30-1.65	600-730	15-25	0.45

Carburized steel 15KhA after being carburized at 900-920°C is subjected to final heat treatment, which consists in hardening from 860°C in oil and tempering at 150-170°C. Steel is supplied in the form of rods. It is used for manufacture of small carburized parts and is substitute for steel 13N2A.

Improved steel 38KhA machines well in annealed state but welds poorly. For imparting final properties parts are hardened from 860°C in oil and tempered at 590°C. Steel is supplied in the form of rods and forgings. It is used for manufacture of pins, shafts, bolts, studs of gears, and other parts.

Ball bearing steel ShKh15 for improvement of workability and preparation of structure for hardening is annealed to granular perlite for 4-6 hours at 780-790°C. It is hardened from 820-840°C in oil or water and is tempered at 180-200°C. It is used for manufacture of parts requiring high resistance to wear, for ball bearings,

and others. It is supplied in the form of rods, bands, and tubing.

Silicon steels, having 1.5-2.0% Si and raised carbon content, possess good resile properties and are used widely for manufacture of springs subjected to heat treatment.

Of greatest application are silicon steels of grades 55SA and 60S2A.

They are supplied in the form of bands, rods, and tapes and are used for manufacture of flat and coil springs. After hardening and medium tempering, they are distinguished by high hardness and elasticity. For instance, steel 60S2A (0.56-0.64% C; 1.6-2.0% Si) after being hardened from 870°C in oil and tempered at 460°C, has following mechanical properties: $\sigma_B = 1300 \text{ MN/m}^2$ (130 kgf/mm²); $\sigma_{0.2} = 1200 \text{ MN/m}^2$ (120 kgf/mm²); $\delta = 5\%$.

In addition to that, silicon steels find wide application for manufacture of parts of electrical and radio equipment.

Manganese steels, containing to 2% manganese, are applied widely as structural material. Manganese increases their strength and hardenability. With small content of carbon (0.1-0.25%) these steels possess high ductility and good weldability, and with raised carbon content (0.60-0.70%) they are hard and elastic.

Chemical composition and mechanical properties of those grades of steel most widely applied in aircraft building are given in Table 8.

Table 8. Chemical Composition and Mechanical Properties of Manganese Steels

Grade	Chemical composition in %		Mechanical properties (not less)	
	C	Mn	σ_B MN/m ²	δ %
10Г2А	0.08-0.17	1.20-1.60	400-580	22
12Г2А	0.12-0.20	2.0-2.4	500-650	18
20ГА	0.18-0.26	1.30-1.60	500-700	10
65Г	0.60-0.70	0.90-1.20	1500-1650	4

Steels 10G2A and 12G2A possess excellent weldability and do not form welding cracks even under very severe conditions of welding.

Steel 10G2A, thanks to high plasticity, is well suited to stamping, bending, and other technological operations. It is applied in annealed or normalized state for welded and stamped parts with ultimate strength up to 400-500 MN/m² (40-50 kgf/mm²). This steel is supplied in the form of thin sheets, tubing, and rods.

Steel 12G2A, in view of raised content of carbon and manganese as compared to steel 10G2A, has higher mechanical properties. Of steel 12G2A are prepared welded and stamped aircraft parts with ultimate strength of $600-900 \text{ MN/m}^2$ ($60-90 \text{ kgf/mm}^2$).

Steel 20GA is applied in aircraft building as material for rivets in vital parts and constructions. The most important merits of rivets of steel 20GA are their good upsetability and high shear strength.

Steel 65G possesses bad workability. It is subjected to heat treatment (hardening and temper), which gives it raised strength and elasticity. It is supplied in the form of rods, wire, and sheets. It is used for manufacture of springs and washers.

Quaternary and More Complex Alloy Steels

Chrome-nickel steels are the most widespread steels in aviation industry. Chromium and nickel as alloy elements complement one another very successfully. Simultaneous introduction to steel of chromium and nickel leads to increase of complex of mechanical properties (strength, hardness, toughness, and ductility) and to increase of hardenability.

The most favorable combination of mechanical properties is observed with content in steel of carbon of from 0.15% to 0.45%, chromium of from 0.5% to 2%, and nickel of from 2 to 5%. By changing the relationship between these elements in steel the most varied properties can be obtained.

Chrome-nickel steels with small content of carbon are carburized and those with raised content of carbon are improved.

Further strengthening of chrome-nickel is attained by additional alloying with small quantities of tungsten or molybdenum.

Deficiencies of chrome-nickel are inclination to temper brittleness and formation of flakes.

Chrome-manganese steels are a substitute for chrome-nickel steels. Raised hardenability in them is attained by introduction of cheap manganese instead of scarce nickel. Additional alloying of them with titanium led to creation of widely-spread carburized chromium-manganese-titanium steels.

Chromium-silicon-manganese steels (Cromansil) have successfully replaced chromium-molybdenum steel, which until relatively recently was one of basic steels in aircraft building. Cromansil possesses high hardness plus good stampability

